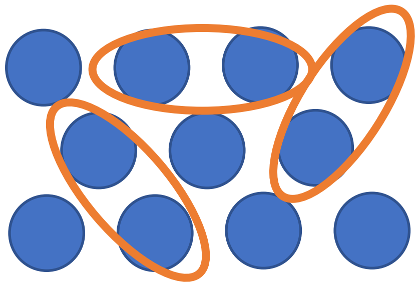
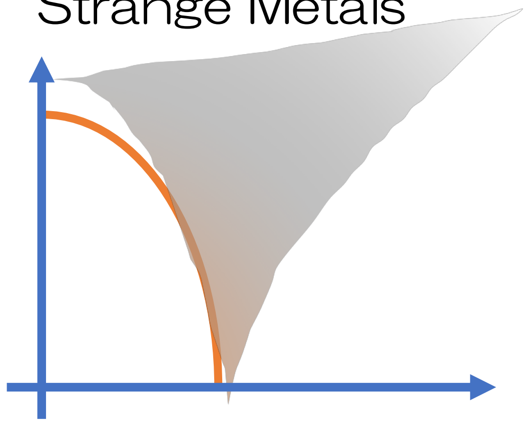
Transport Signatures of strange metals (Part II)

ASCE Summer School



Quantum Spin Liquids

Strange Metals

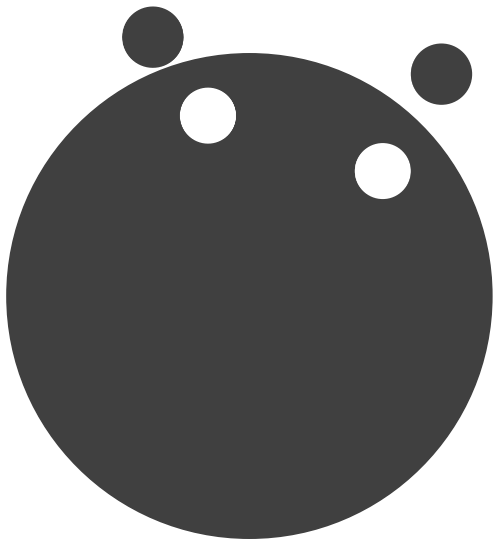


Unconventional superconductor = doped Mott insulator ~ doped spin liquid

I am not sure there are any really clear examples, despite exhaustive searches. More recent ideas have explored spin liquids embedded in a sea of electrons, orbitally specific Mottness and so on…

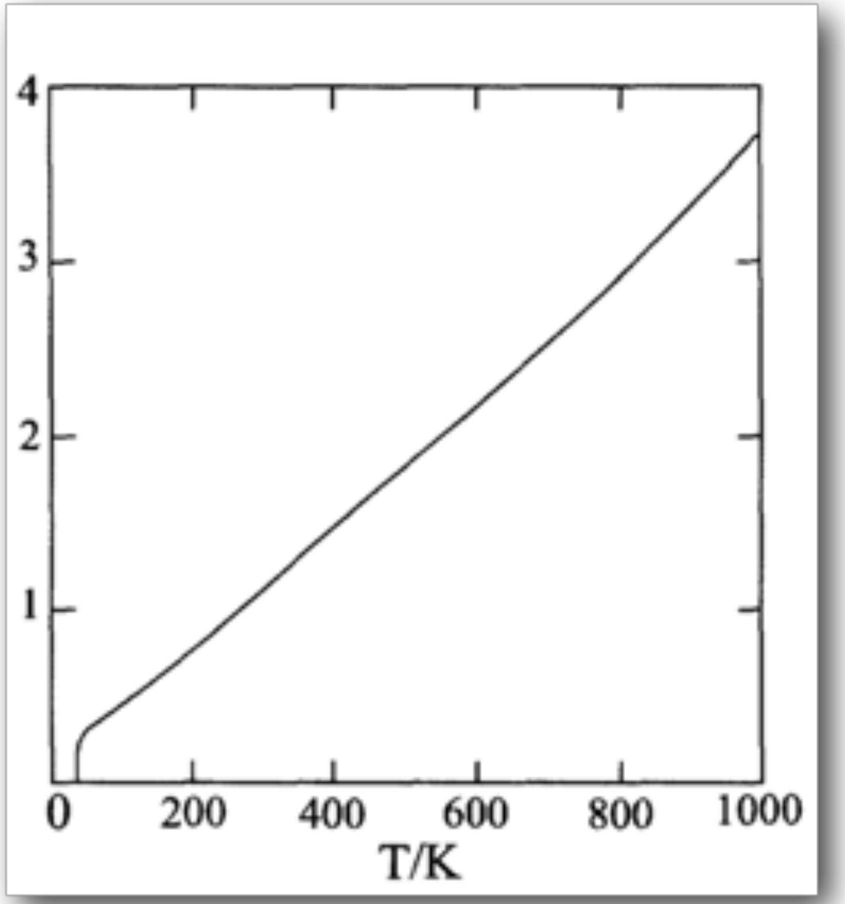
A crash course in Strange metals

T-linear resistivity & the breakdown of the quasiparticle picture

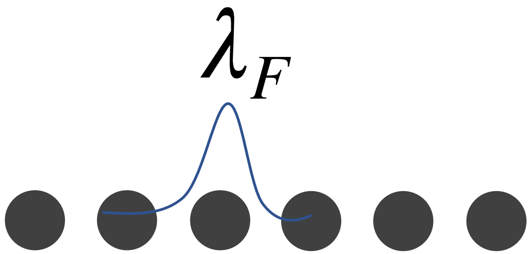


$$\frac{\hbar}{\tau} \propto (k_B T)^2$$

Fermi liquid theory

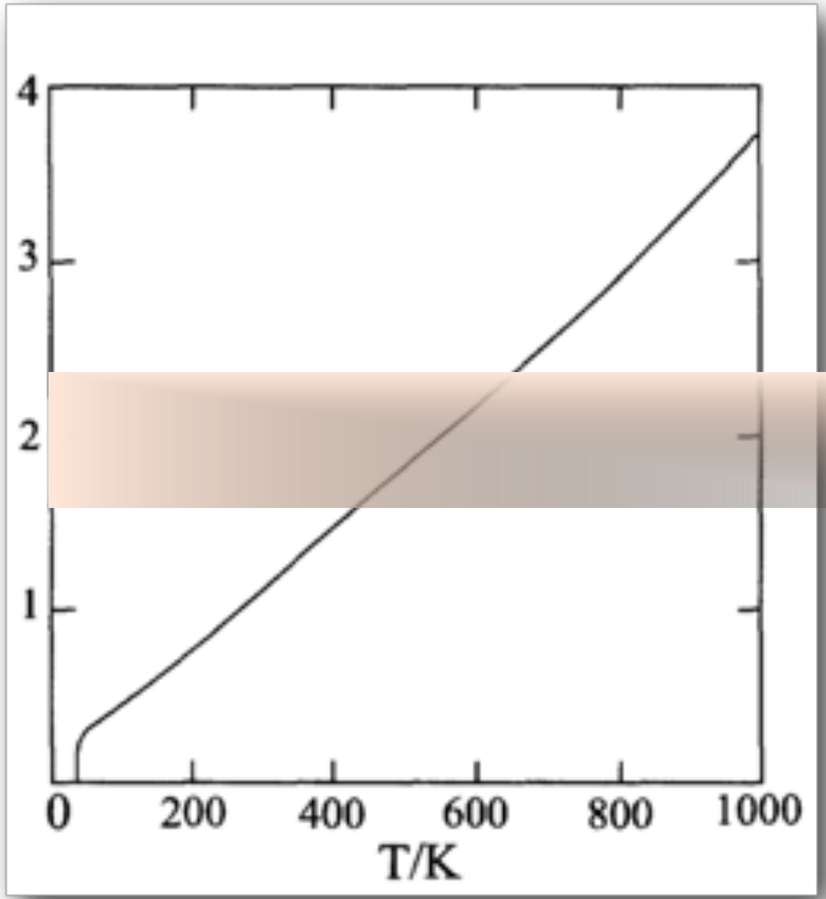


T-linear resistivity & the breakdown of the quasiparticle picture

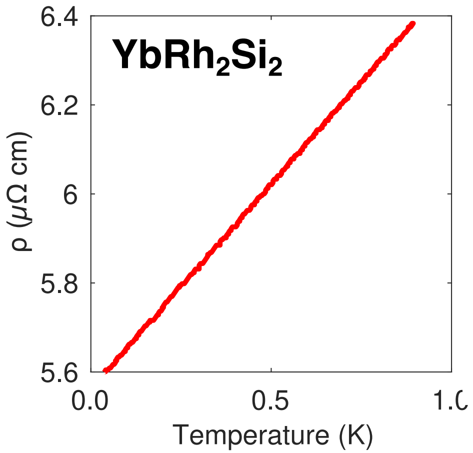


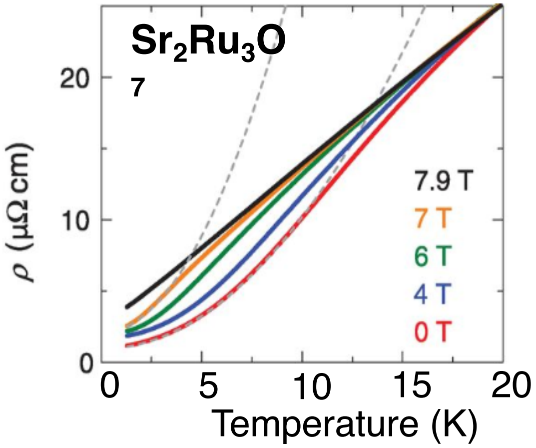
$k_F l \sim 1$

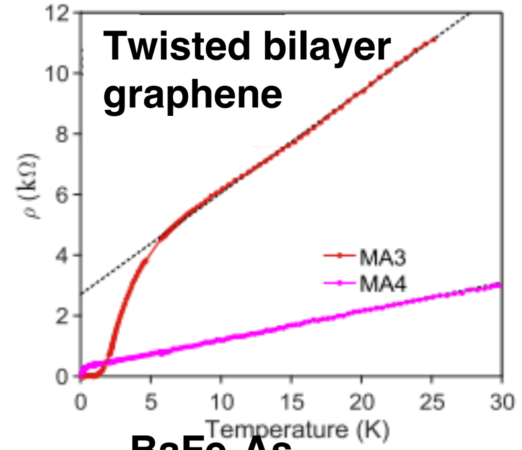
Mott-Ioffe-Regel limit

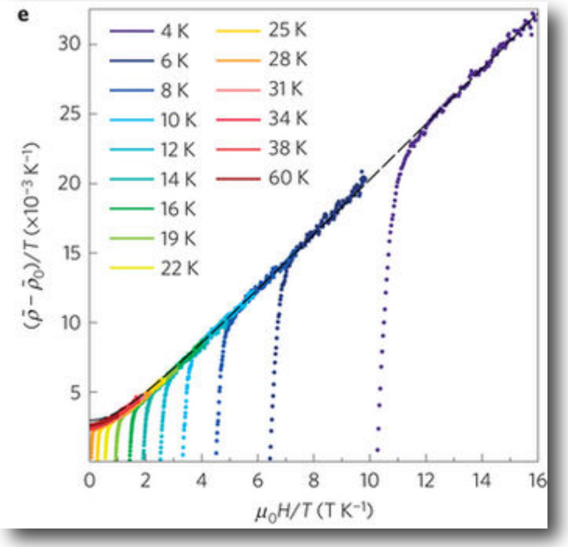


T-linear resistivity & the absence of quasiparticles

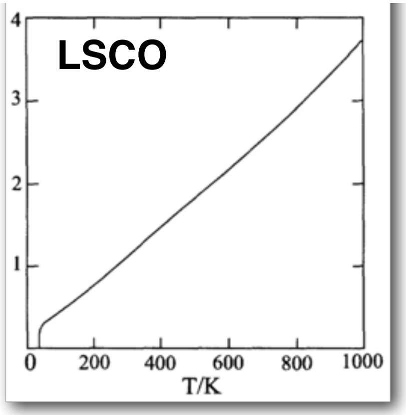


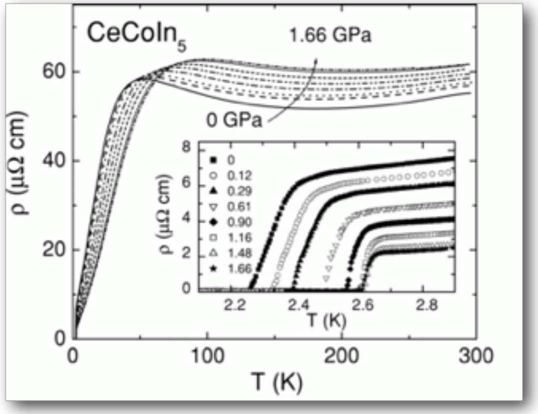




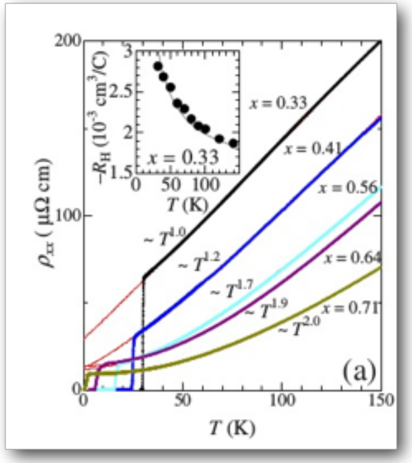


Hayes, JGA, Nature Physics 2016



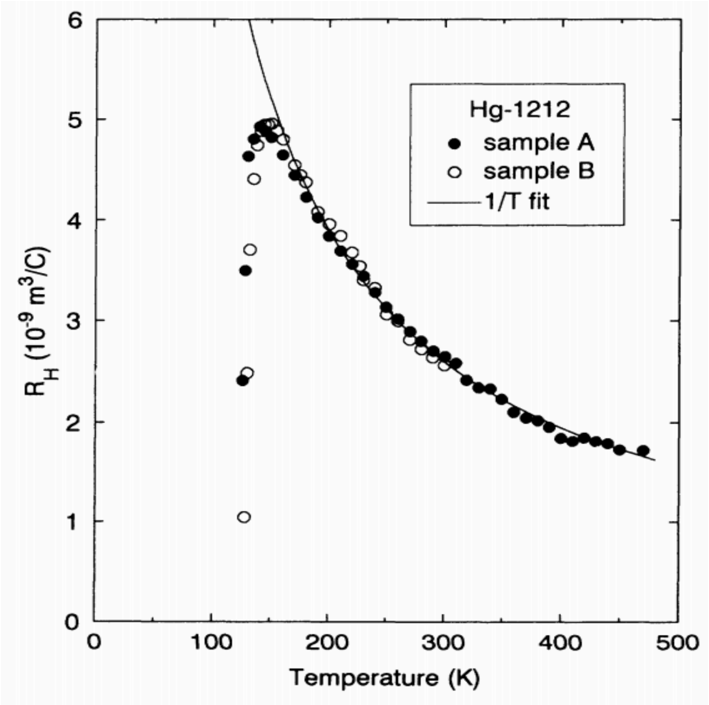


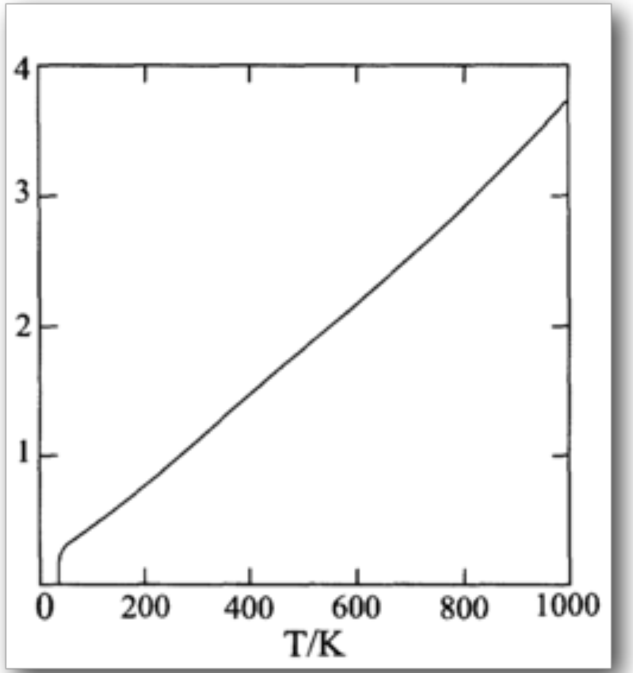
BaFe$_2$As$_2$

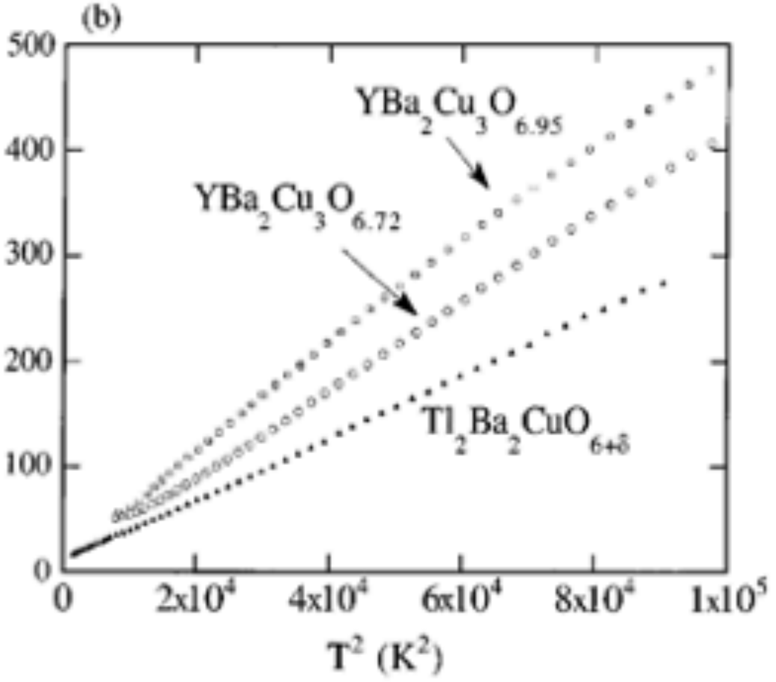


The temperature dependent Hall angle

Hg-1212 cuprate



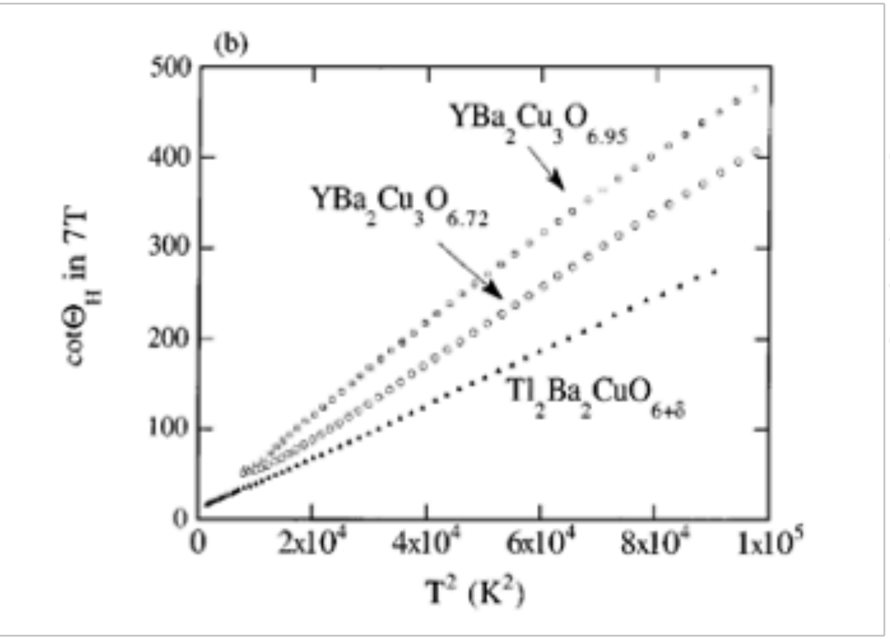




$cot(\Theta_H) \sim 1/\tau \sim T^2$

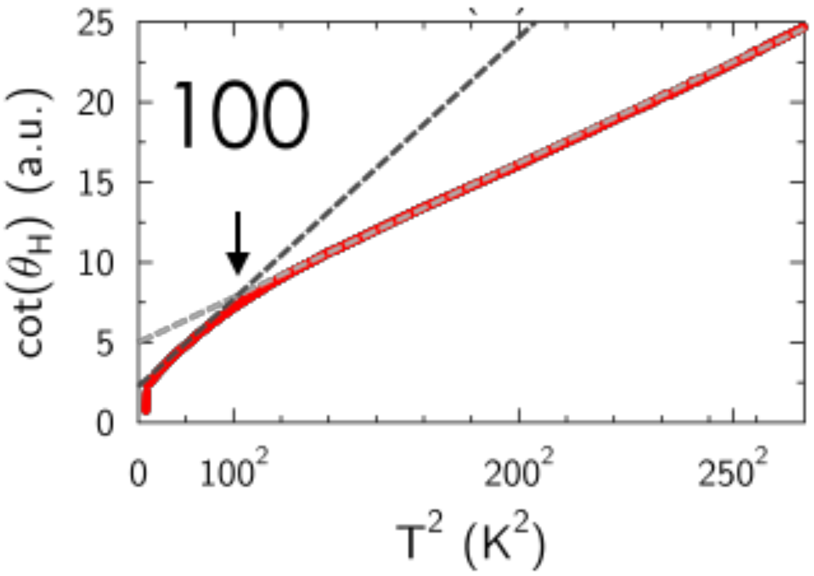
The temperature dependent Hall angle

cuprates



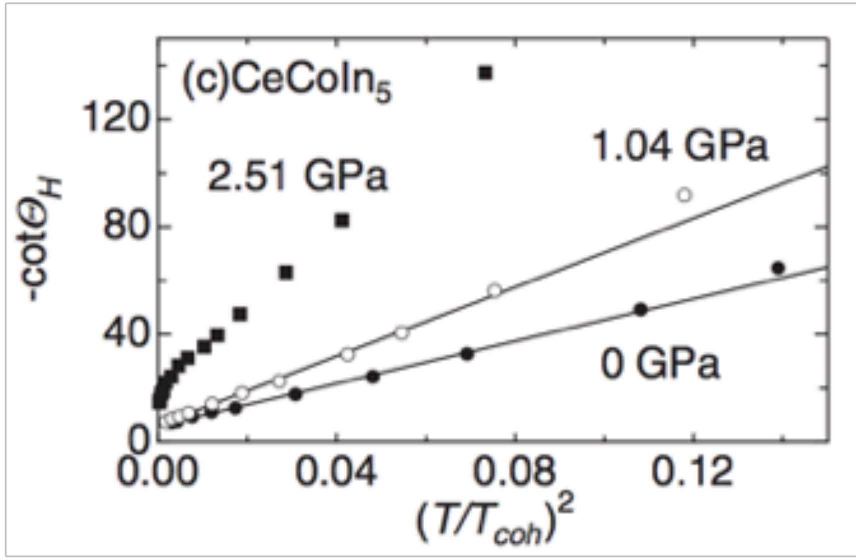
Mackenzie et al.
PRB 1996

pnictides



Hayes,JGA et al.
(unpublished)

heavy fermions



Nakajima et al.
JPSJ 2006

Temperature dependent Hall number

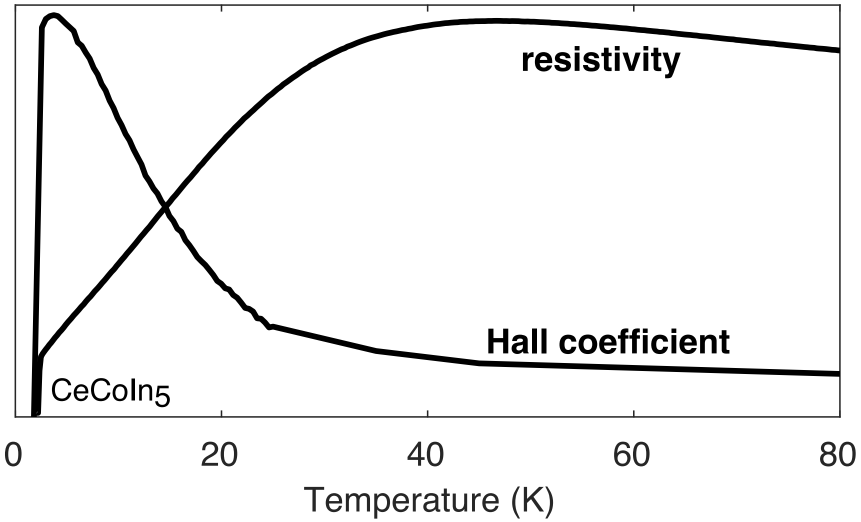
$$\rho = \begin{bmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{yx} & \rho_{yy} \end{bmatrix}$$

Typically Hall coefficient (R_H)
is proportional to carrier density

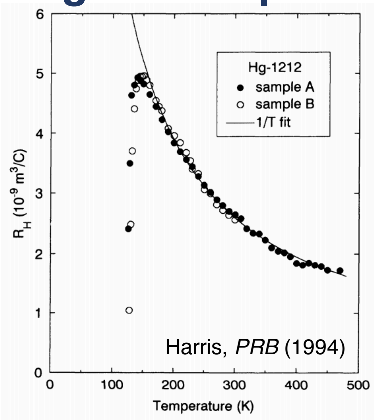
Non-Fermi liquids:

$\boldsymbol{\rho}_{xx} \sim T$

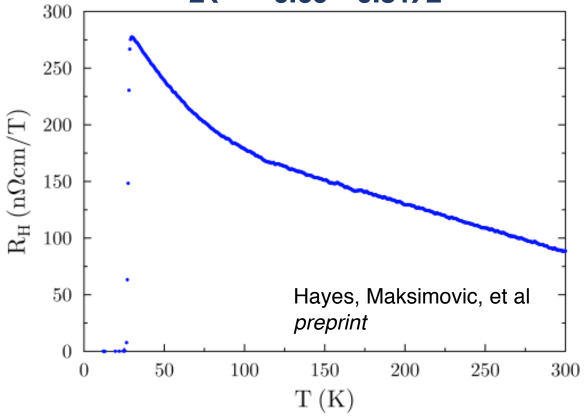
$R_H = \boldsymbol{\rho}_{xy}/B \sim 1/T$



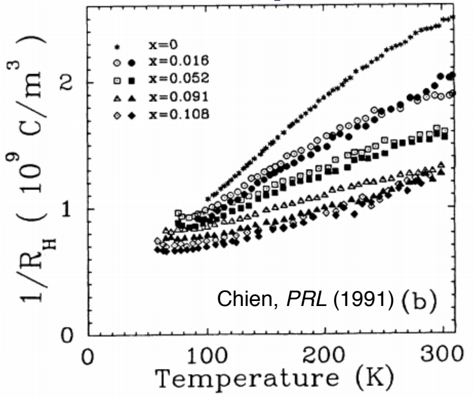
Hg-1212 cuprate



$BaFe_2(As_{0.69}P_{0.31})_2$



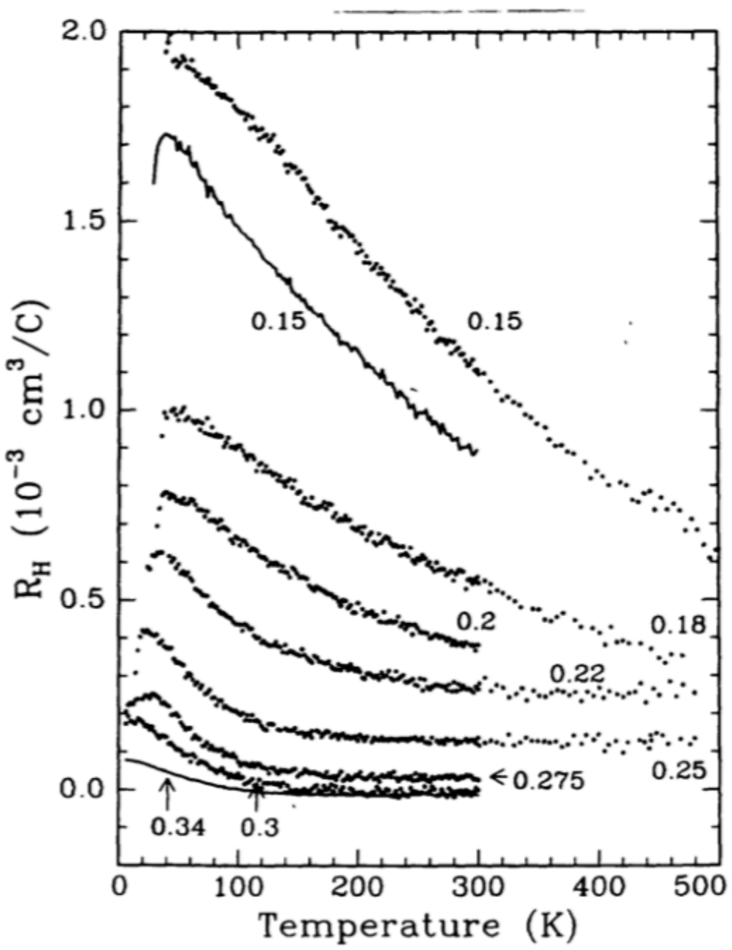
YBCO cuprate



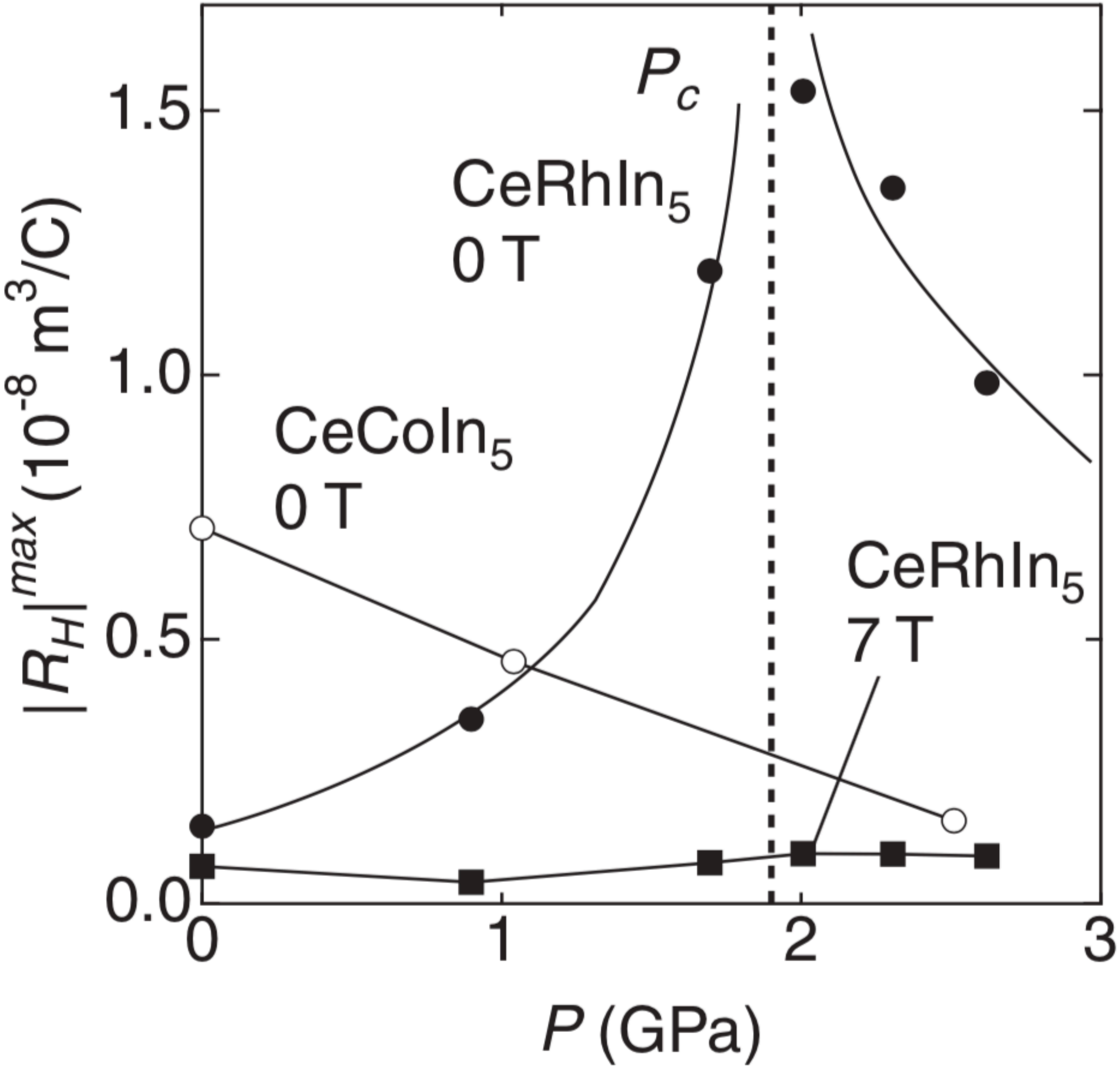
Cuprate Hall effect

- Chien *PRL* (1991)
- Hwang (1992)
- Jiang *PRL* (1992)
- Lan *PRB* (1994)
- Rice *PRB* (1991)
- Xiao *PRB* (1992)
- Kendziora *PRB* (1992)
- Bucher *PRL* (1993)
- Jiang *PRB* (1993)
- Meng *Physica C* (1993)
- . . . . . .

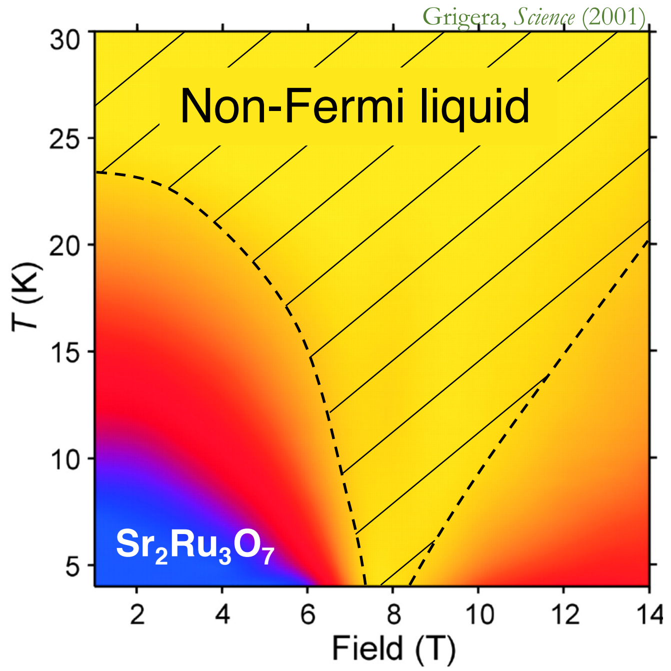
Scaling?

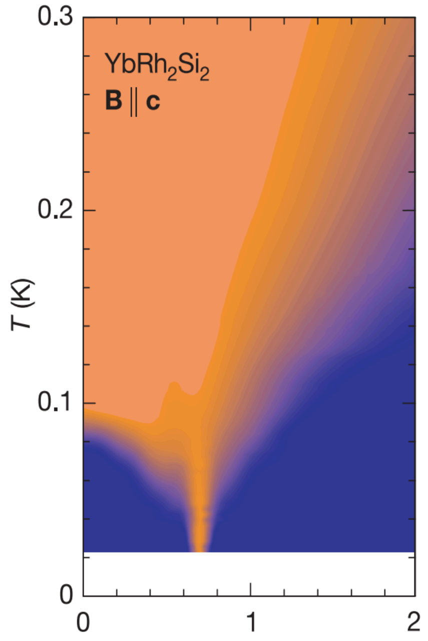


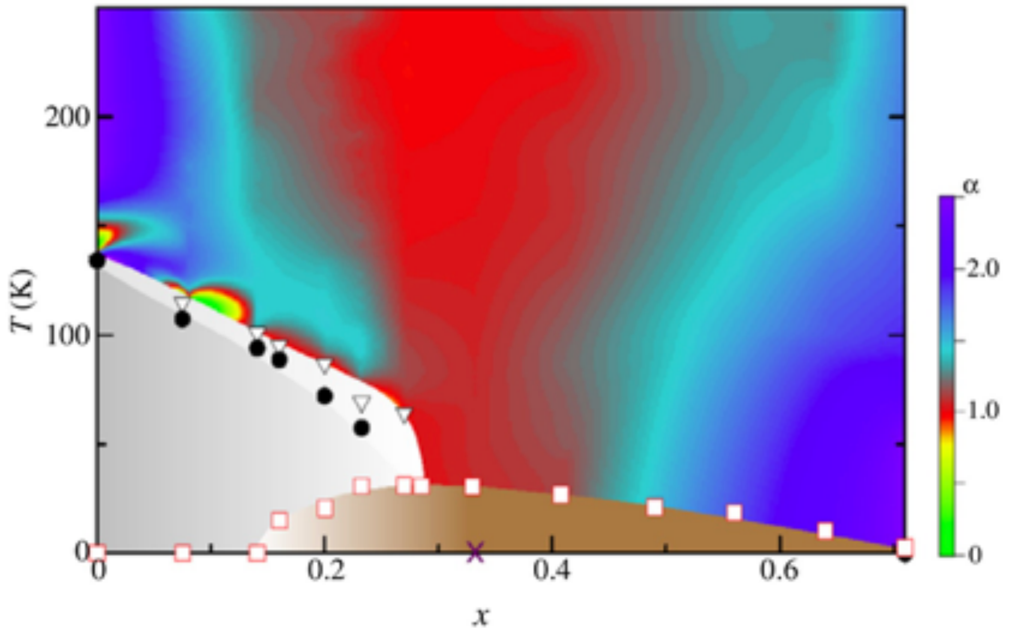
HY Hwang et al PRL 1994



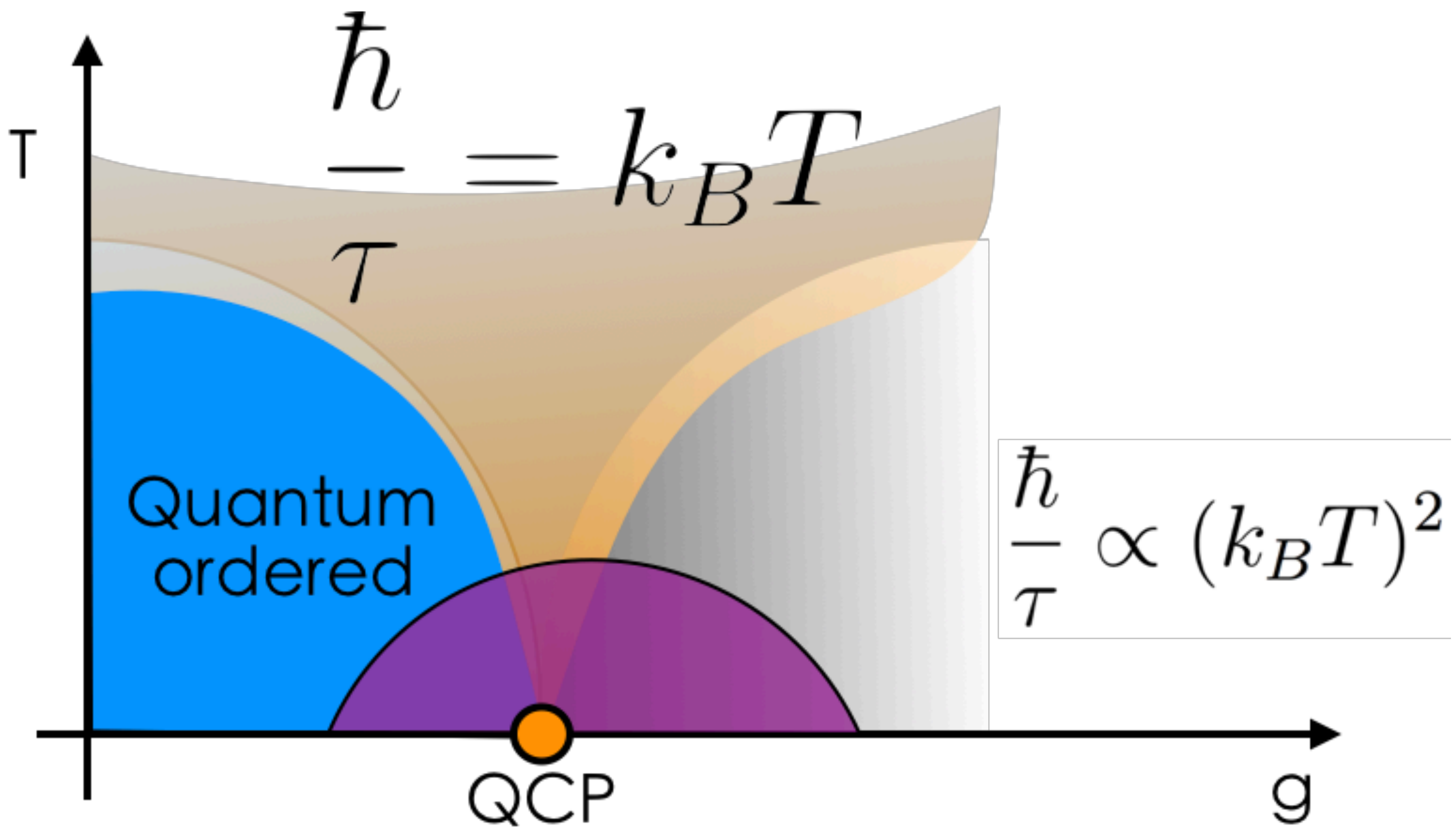
The role of quantum critical points





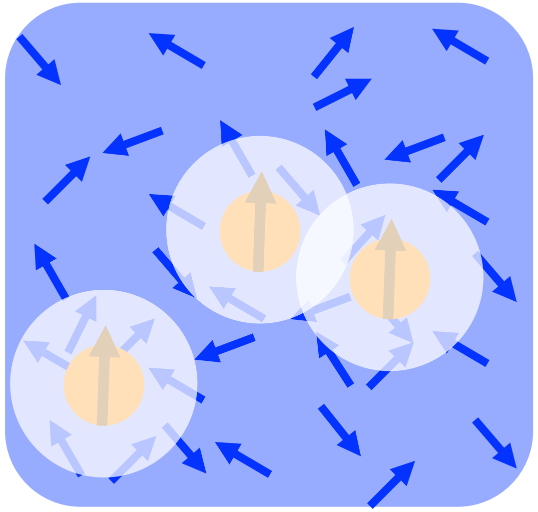


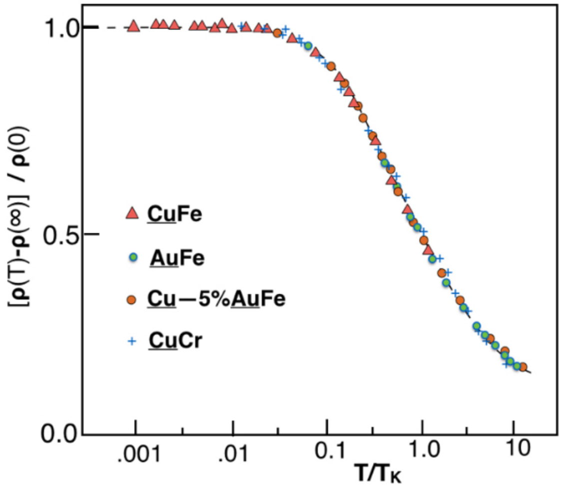
The role of quantum critical points



Introduction to CeCoIn5

From Kondo impurities to Kondo lattice



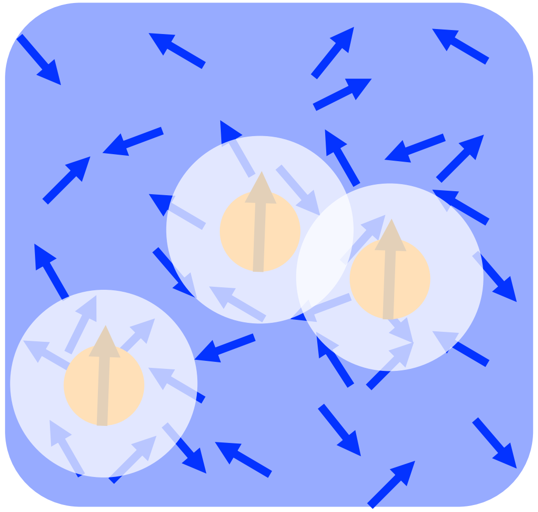


R. H. White and T. H. Geballe

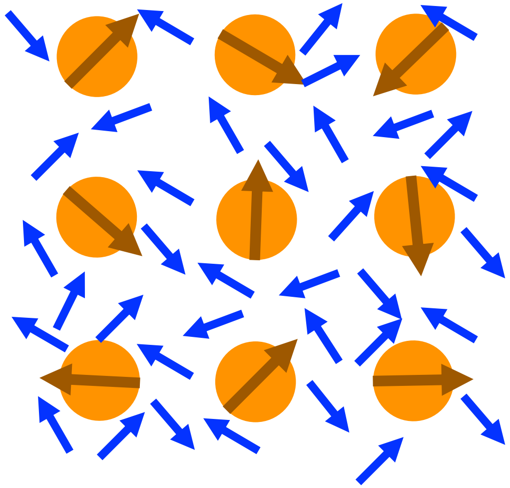
A dense conduction sea with a few local moments eg. Cu with Fe

J. Kondo (1964)

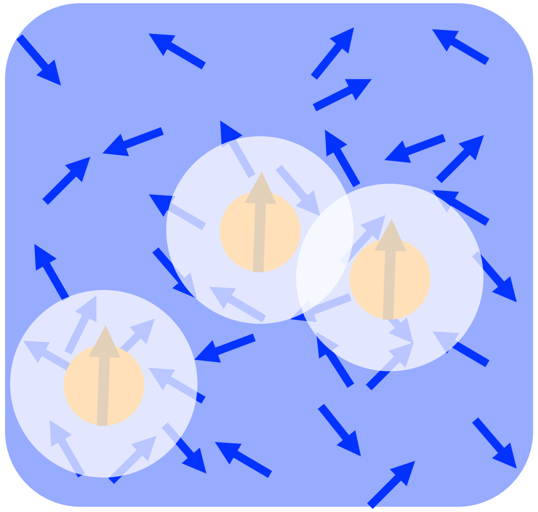
From Kondo impurities to Kondo lattice



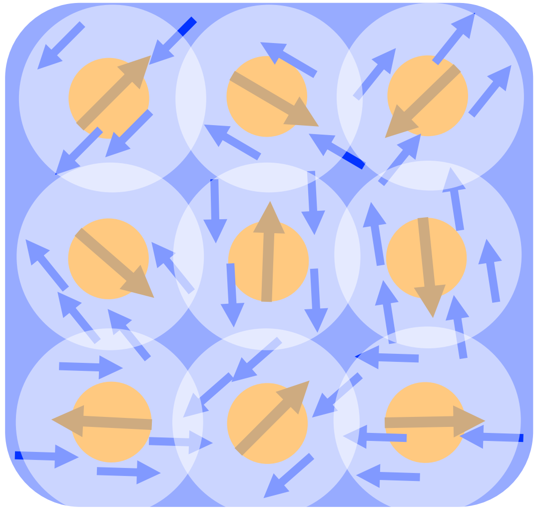
Kondo singlets
in the Kondo impurity model



From Kondo impurities to Kondo lattice

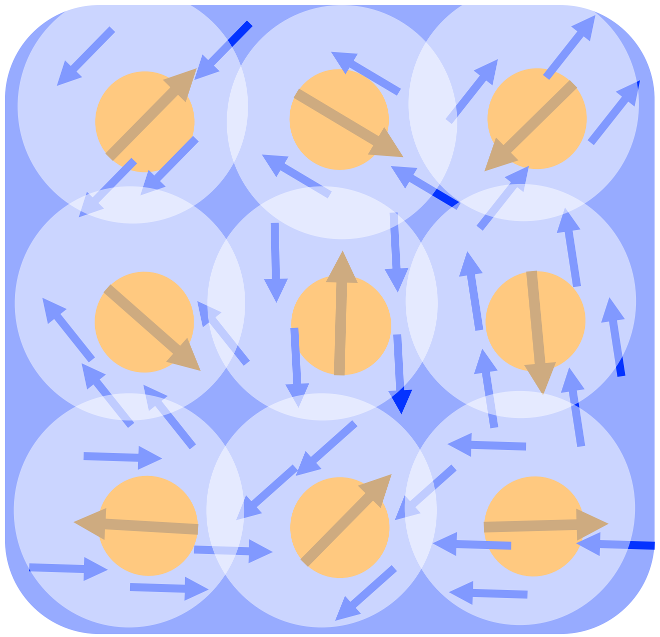


Kondo singlets forming
in the Kondo impurity model

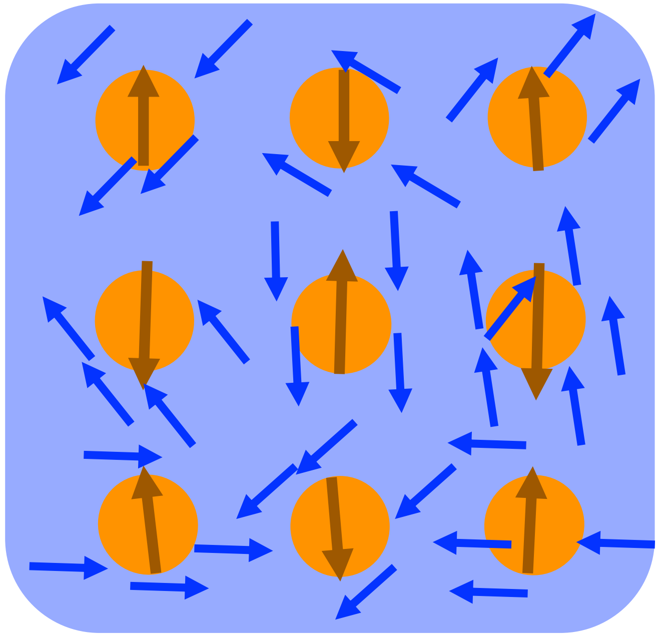


Lattice of Kondo singlets in
the Doniach model

From Kondo impurities to Kondo lattice

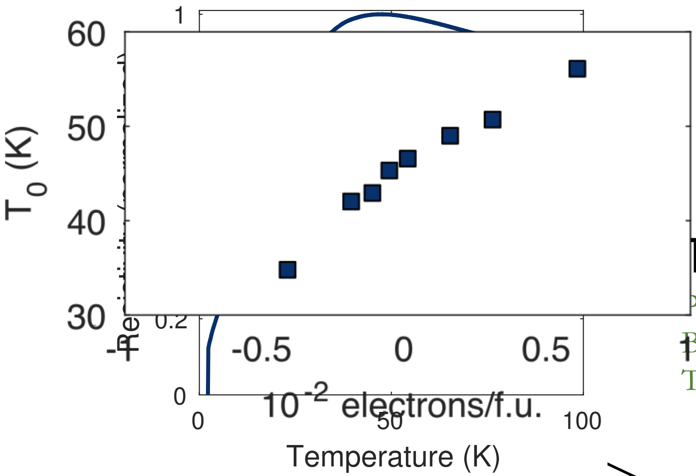


Kondo metal



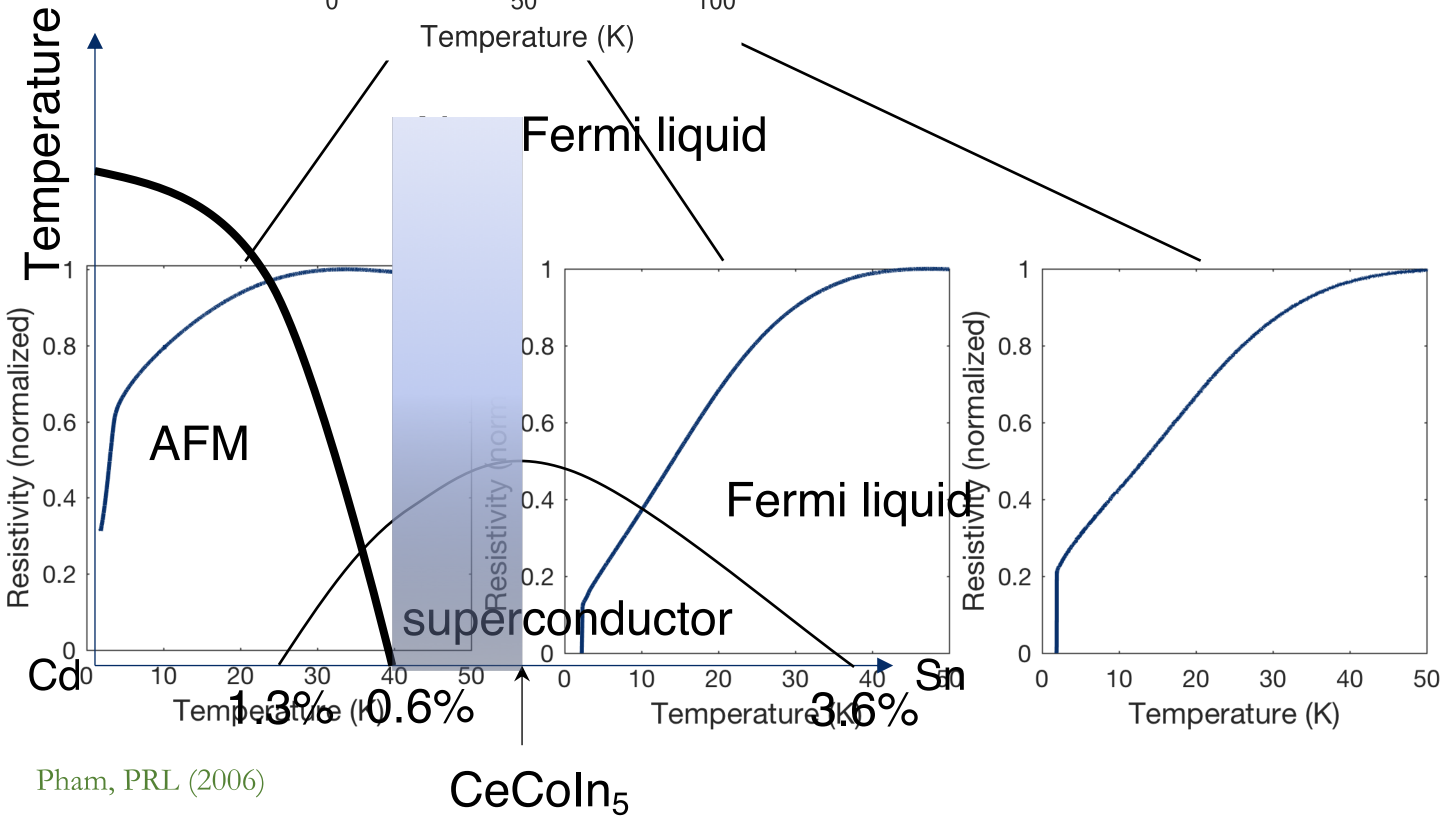
AFM (some local moment metal)

Introduction to $CeCoIn_5$



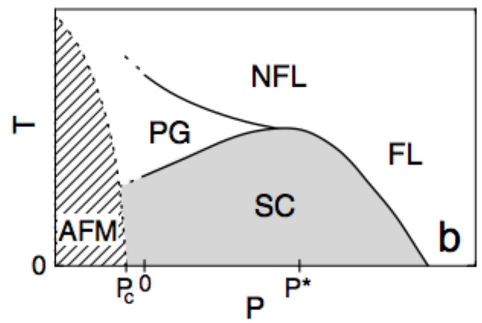
This material is close to a QCP

Petrovic, *PRL* (2003)
Bianchi, *PRL* (2003)
Tokiwa, *PRL* (2013)

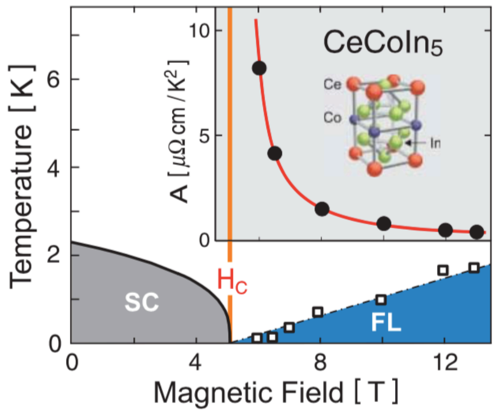


Pham, PRL (2006)

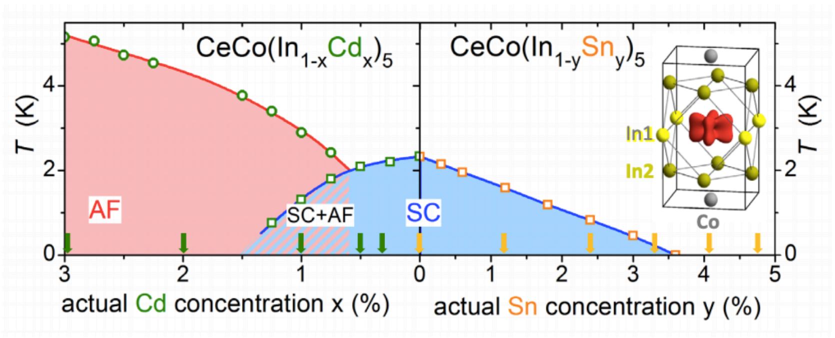
pressure



magnetic field



doping



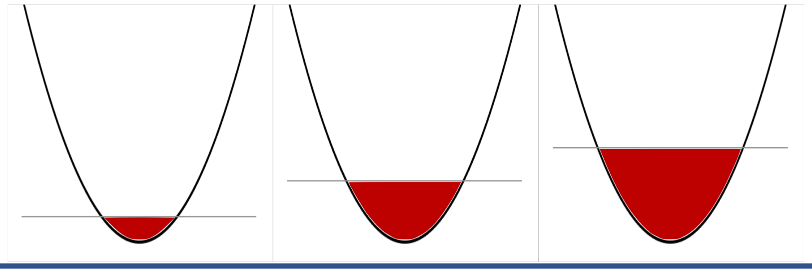
Two important questions

WHAT IS THE NATURE OF THE QUANTUM CRITICAL POINT?

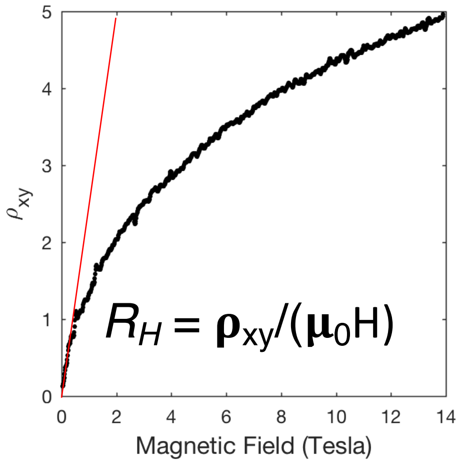
WHAT DOES THIS TELLS US ABOUT THE ORIGIN OF THE STRANGE METAL?

A detailed look into the Hall number of CeCoIn5

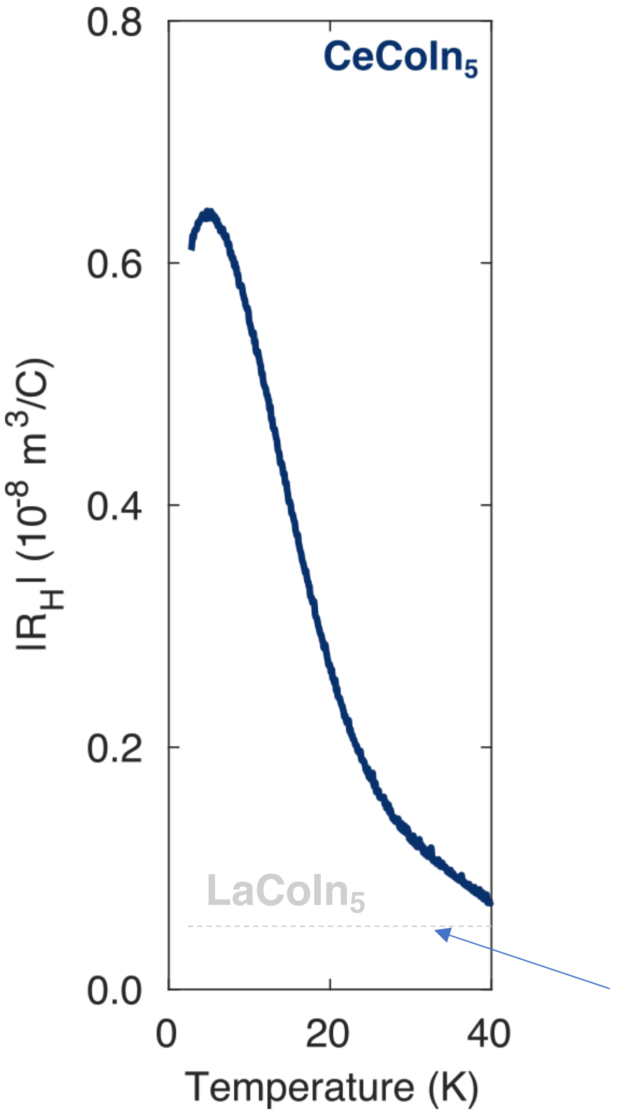
Hall coefficient: vs. doping



Typically R_H varies monotonically with carrier doping

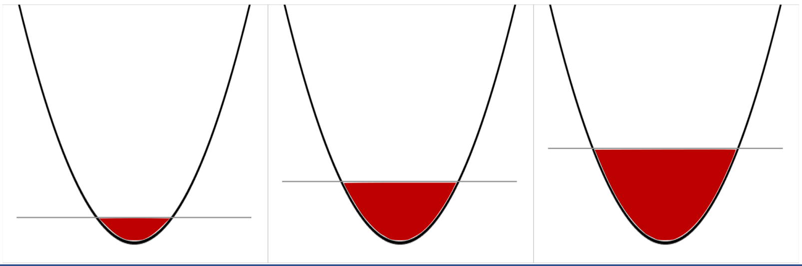


R_H(H ⟶ 0)
reflects carrier density of a single band

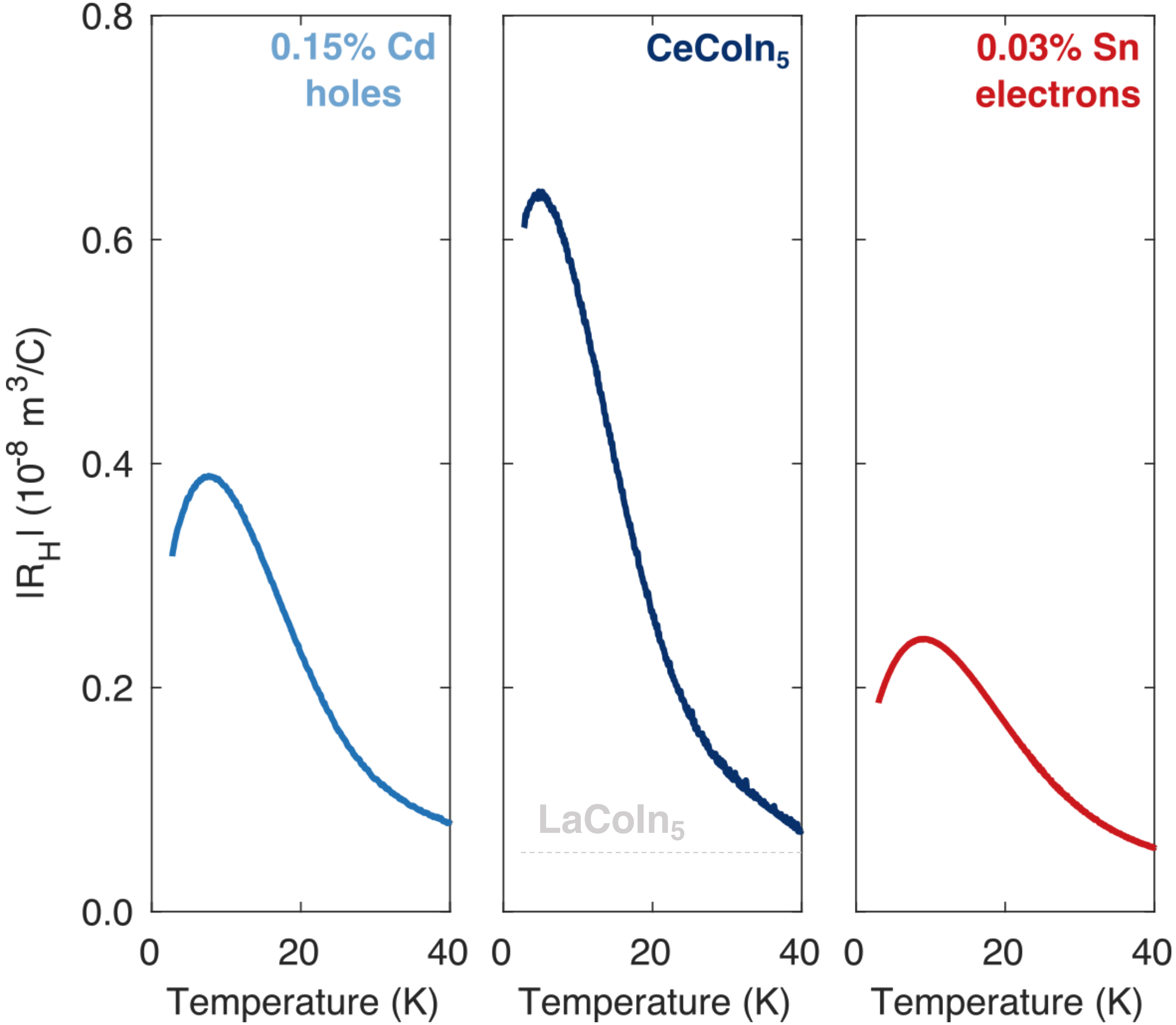


A Fermi liquid!

Hall coefficient: vs. doping

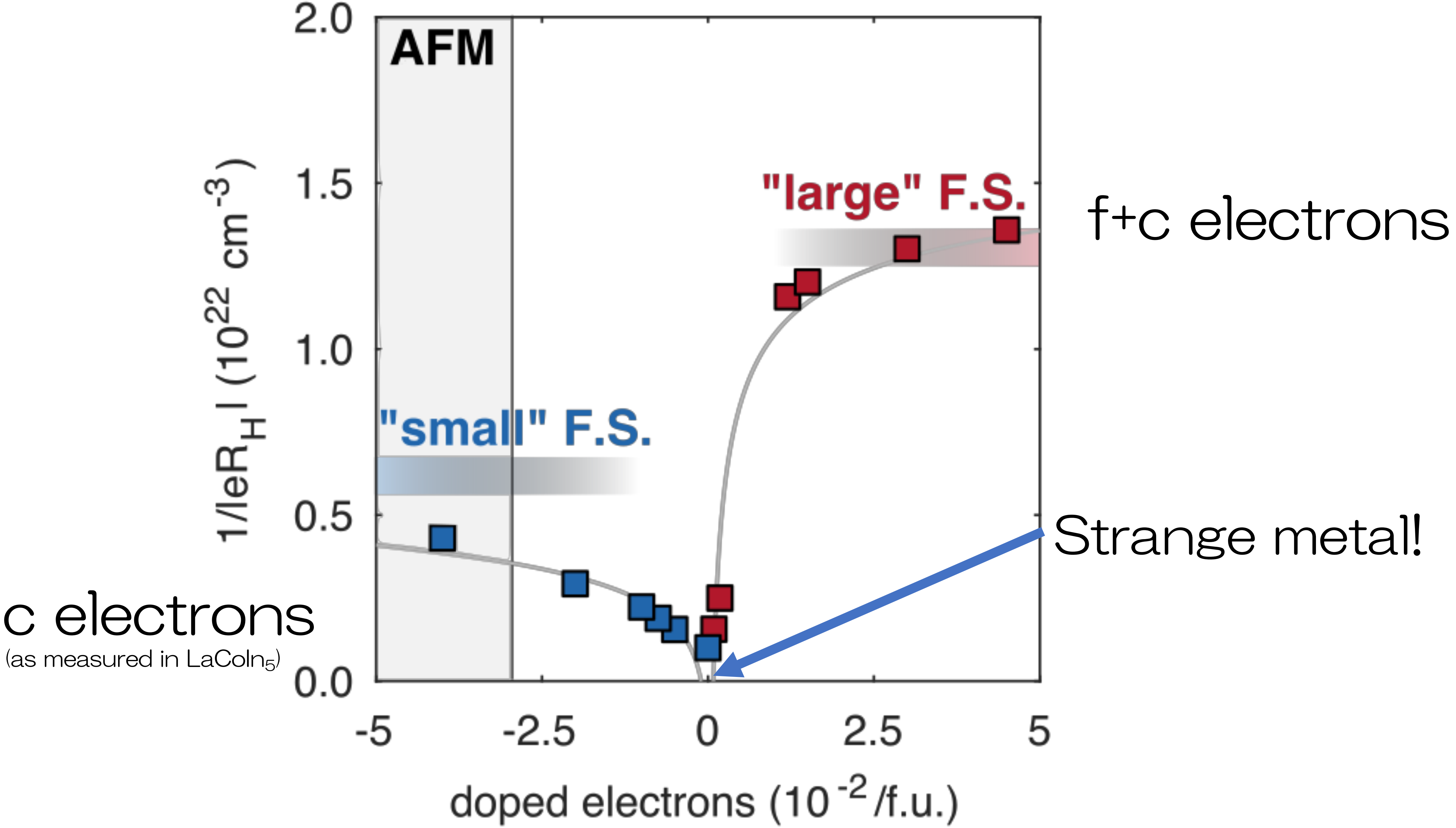


Naively R_H varies monotonically with carrier doping



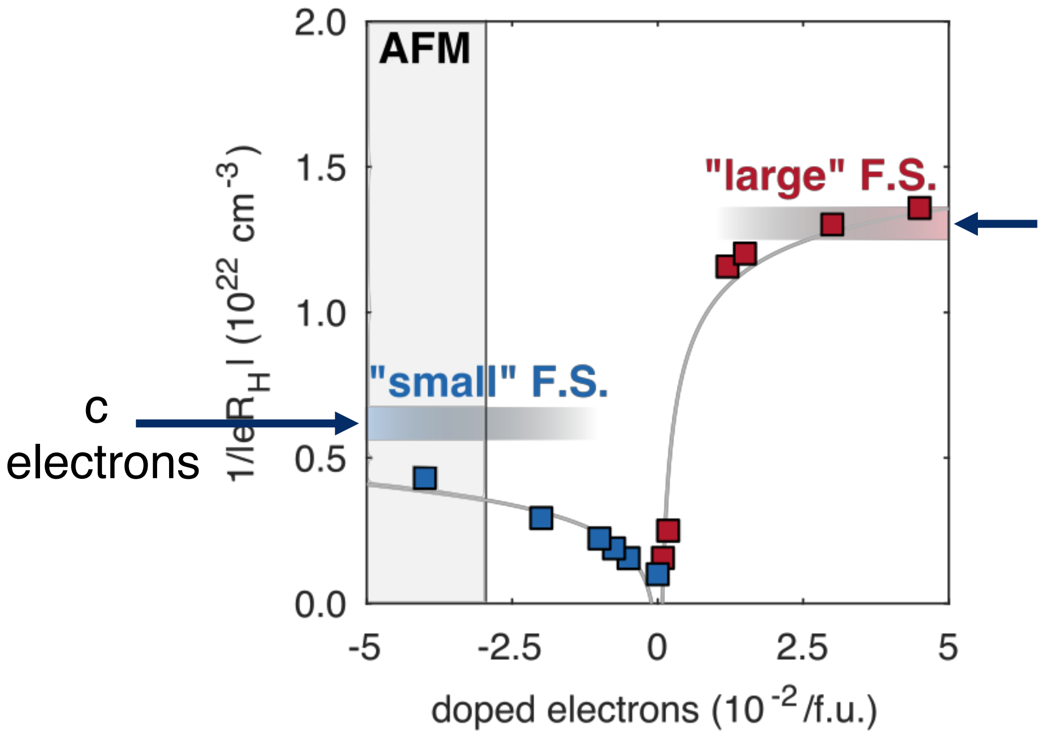
Inconsistent with rigid band structure.

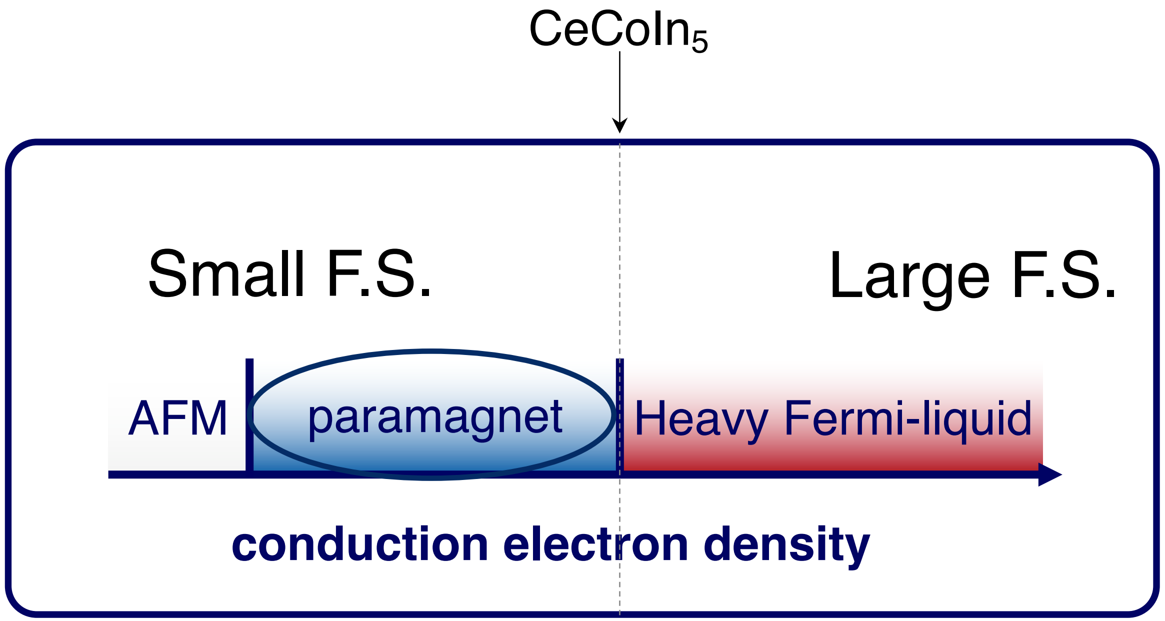
Singular?



AFM
"large" F.S.
"small" F.S.
f+c electrons
Strange metal!
c electrons
(as measured in $LaCoIn_5$)
$1/|eR_H|$ (10^{22} cm^{-3})
doped electrons (10^{-2}/f.u.)
2.0
1.5
1.0
0.5
0.0
-5
-2.5
0
2.5
5

Quantum Critical Point: Fermi surface volume transition



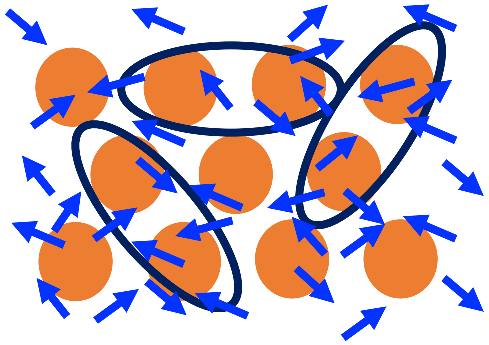


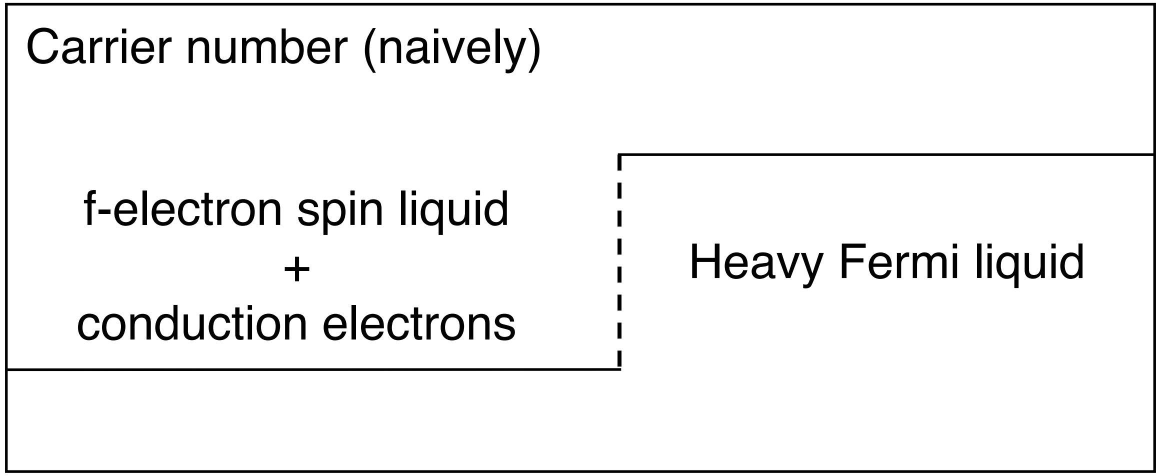
f-electrons localize – but with no magnetic ordering

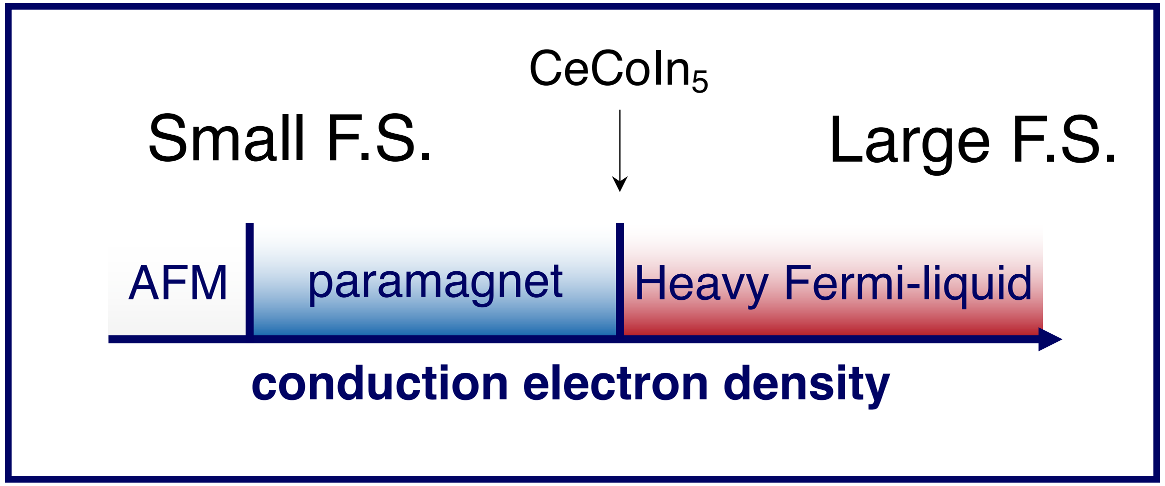
R_H divergence close to the QCP
Vanishing quasiparticles?

What happened to the f-electrons? A possible FL*-FL transition.

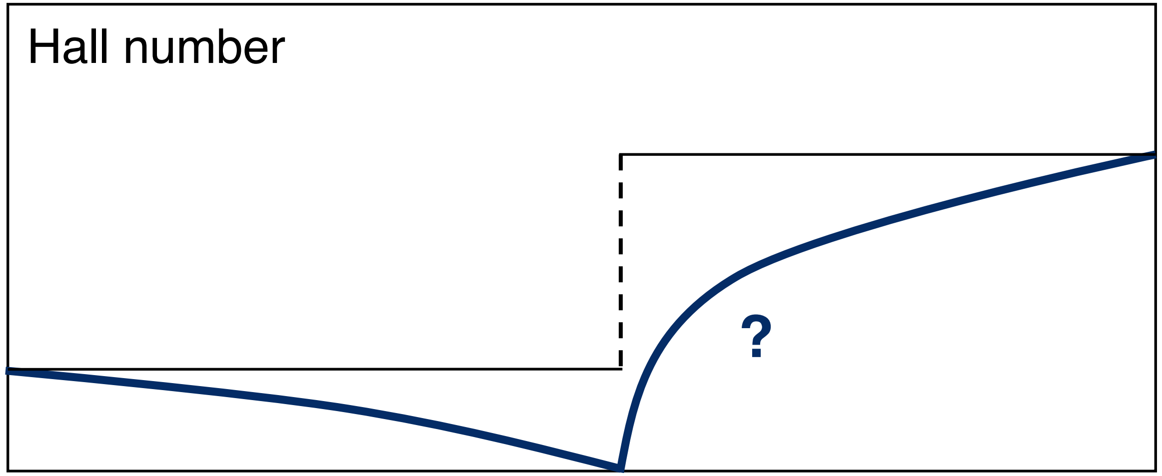
Theoretical precedent: an FL* – FL transition

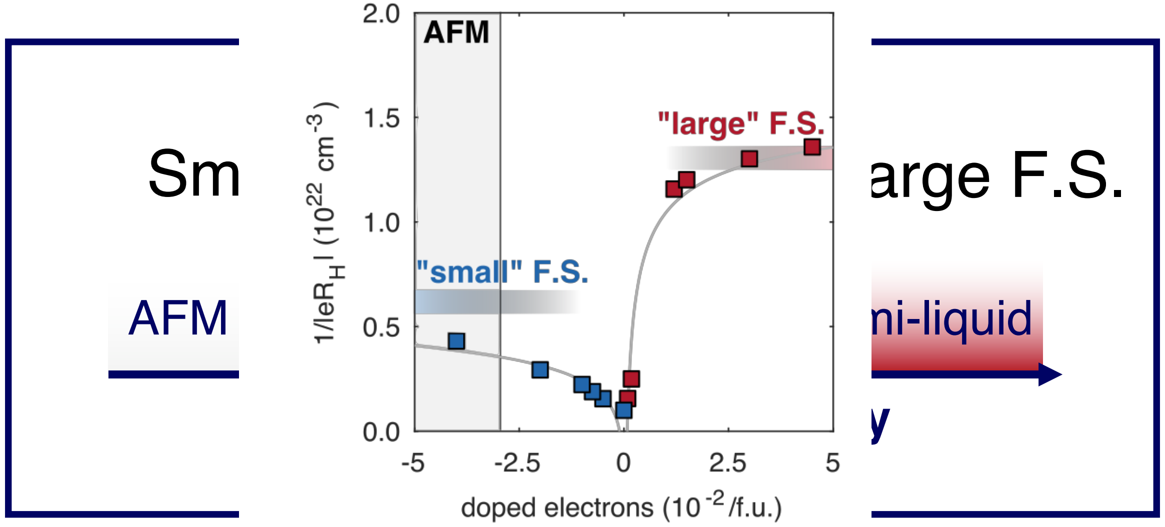






Theoretical precedent: an FL* – FL transition

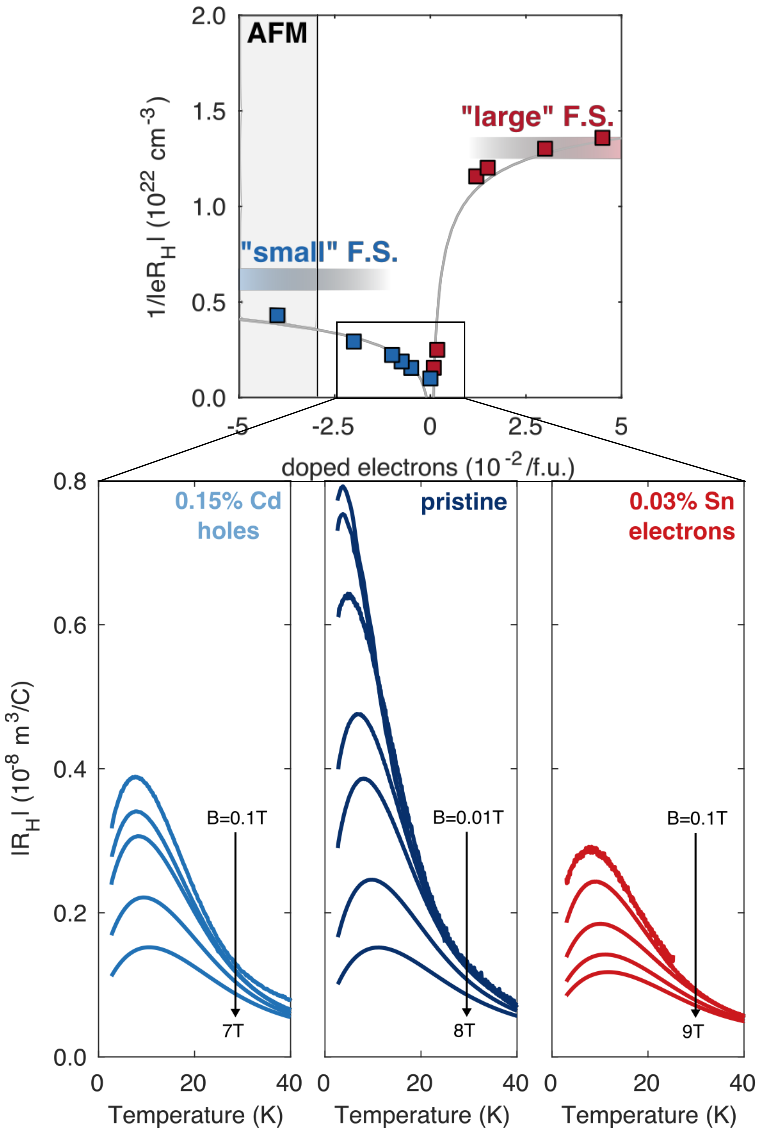


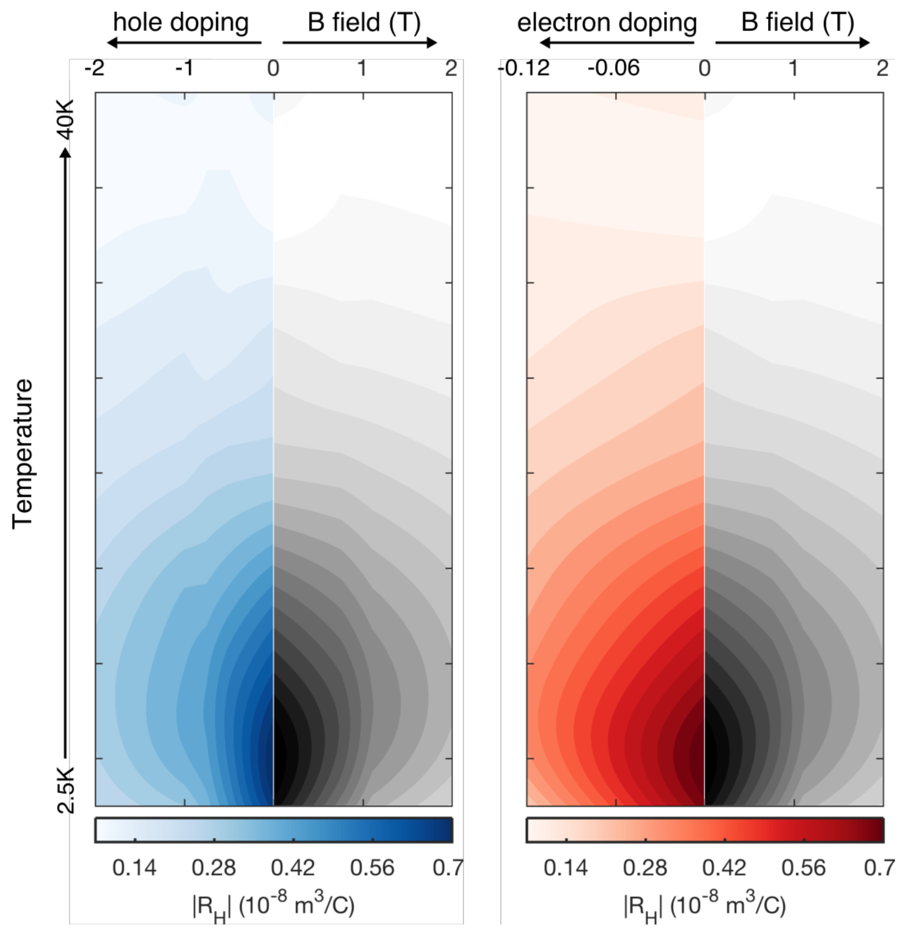


Why does the Hall number collapse in $CeCoIn_5$?

Hall as a function of field

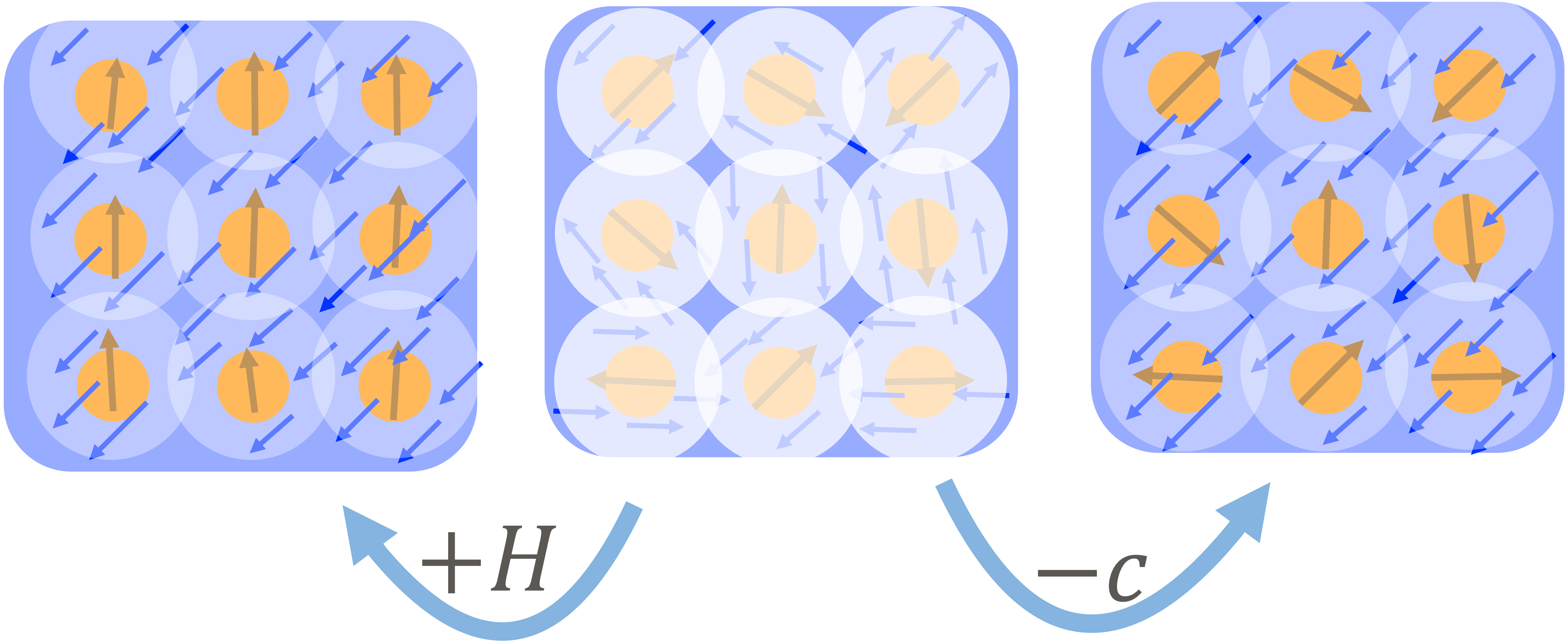
Hall effect vs. magnetic field – single vanishing energy scale?





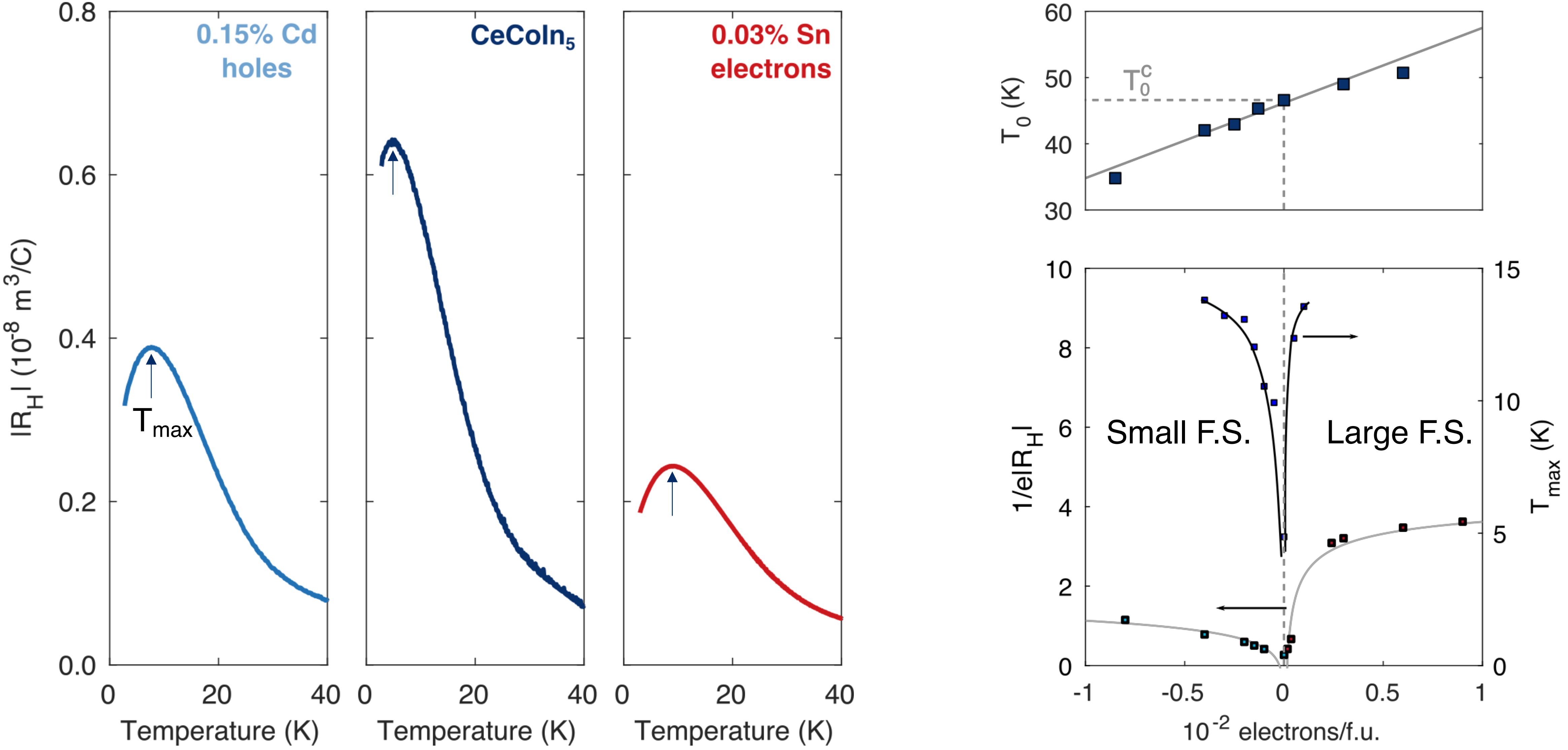
R_H responds identically to…
electron-doping
hole-doping
magnetic field

Could fluctuations in the hybridization field be destroying quasiparticles?

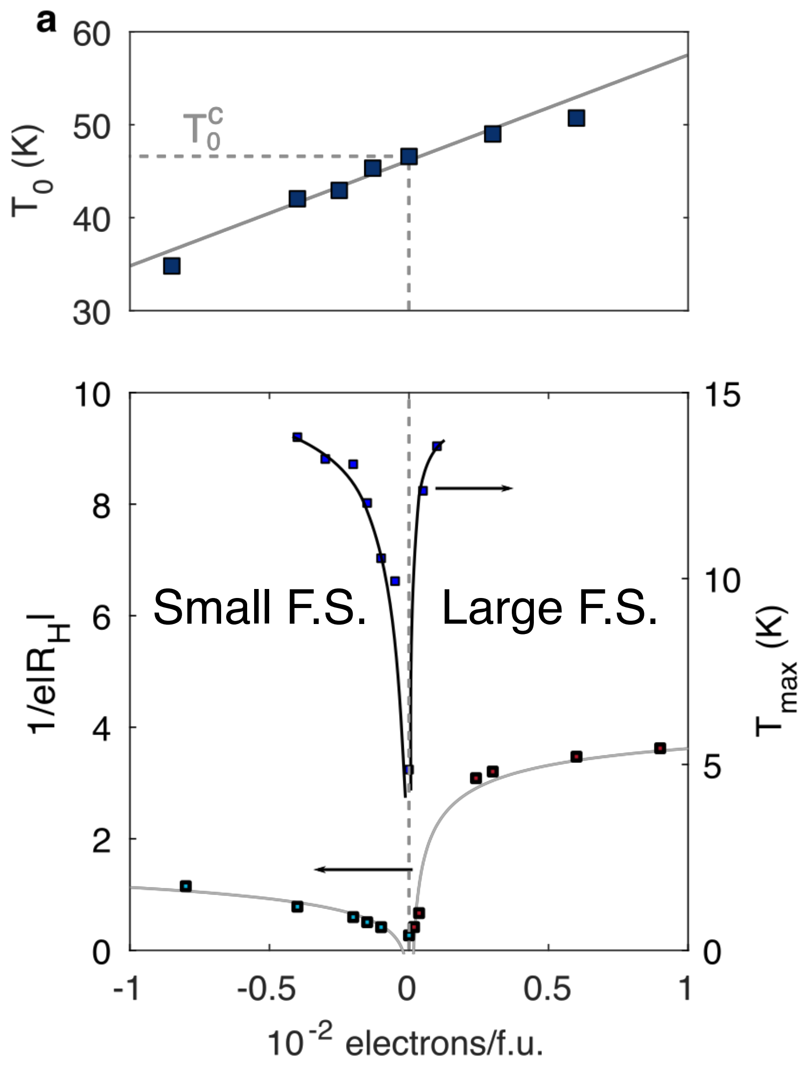


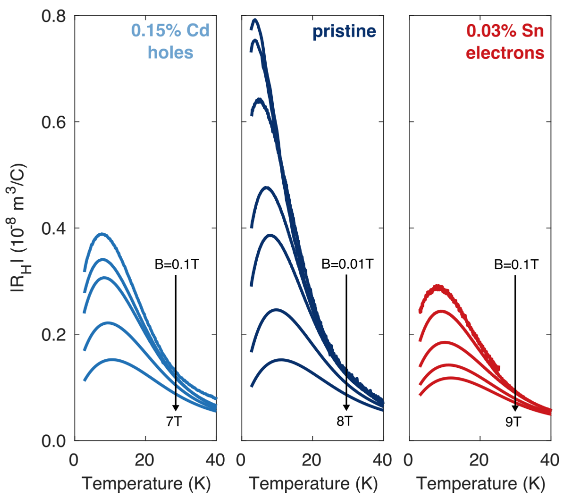
Is there a single energy scale, and what is it?

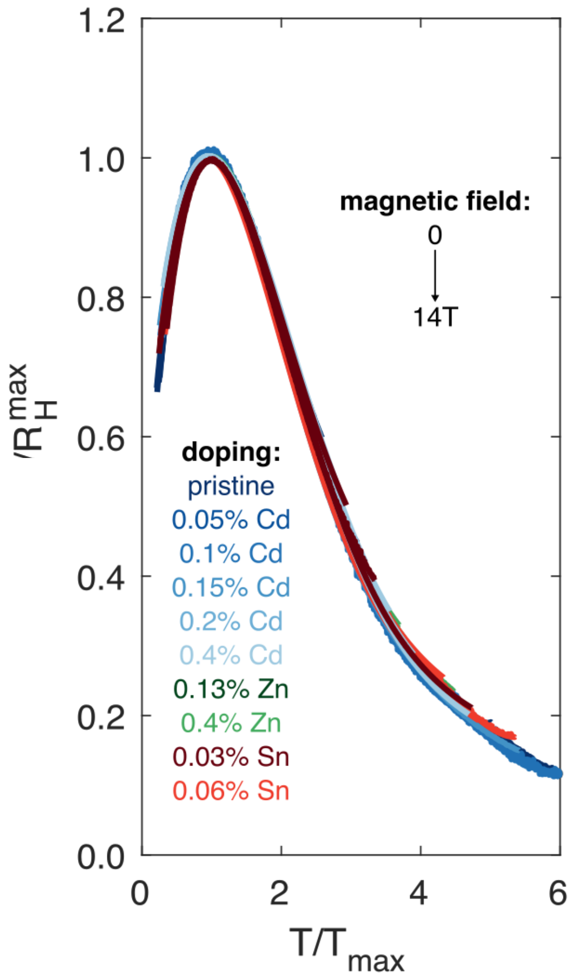
Hall coefficient measures collapsing energy scale



Universality in the non-Fermi liquid Hall effect

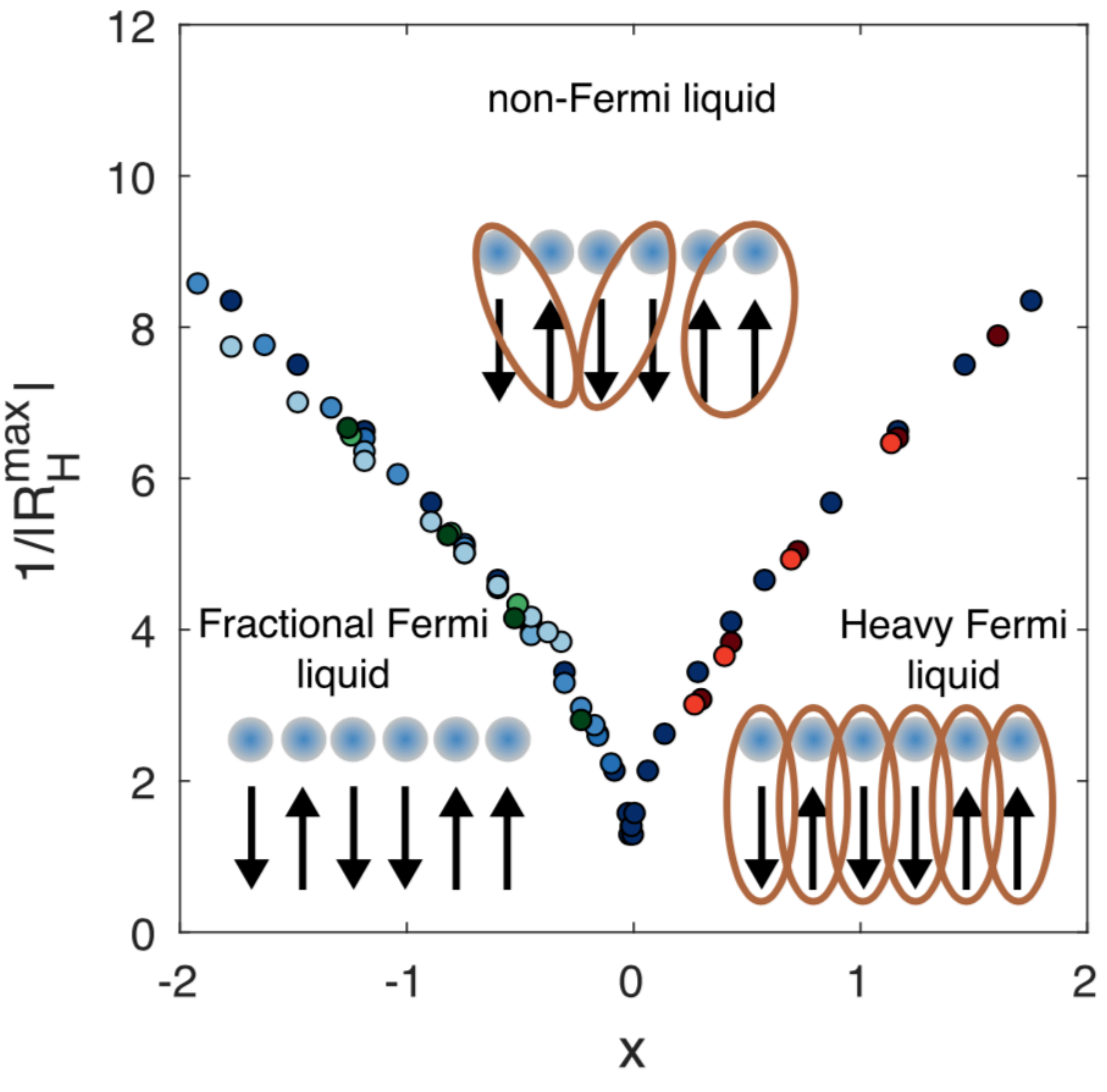


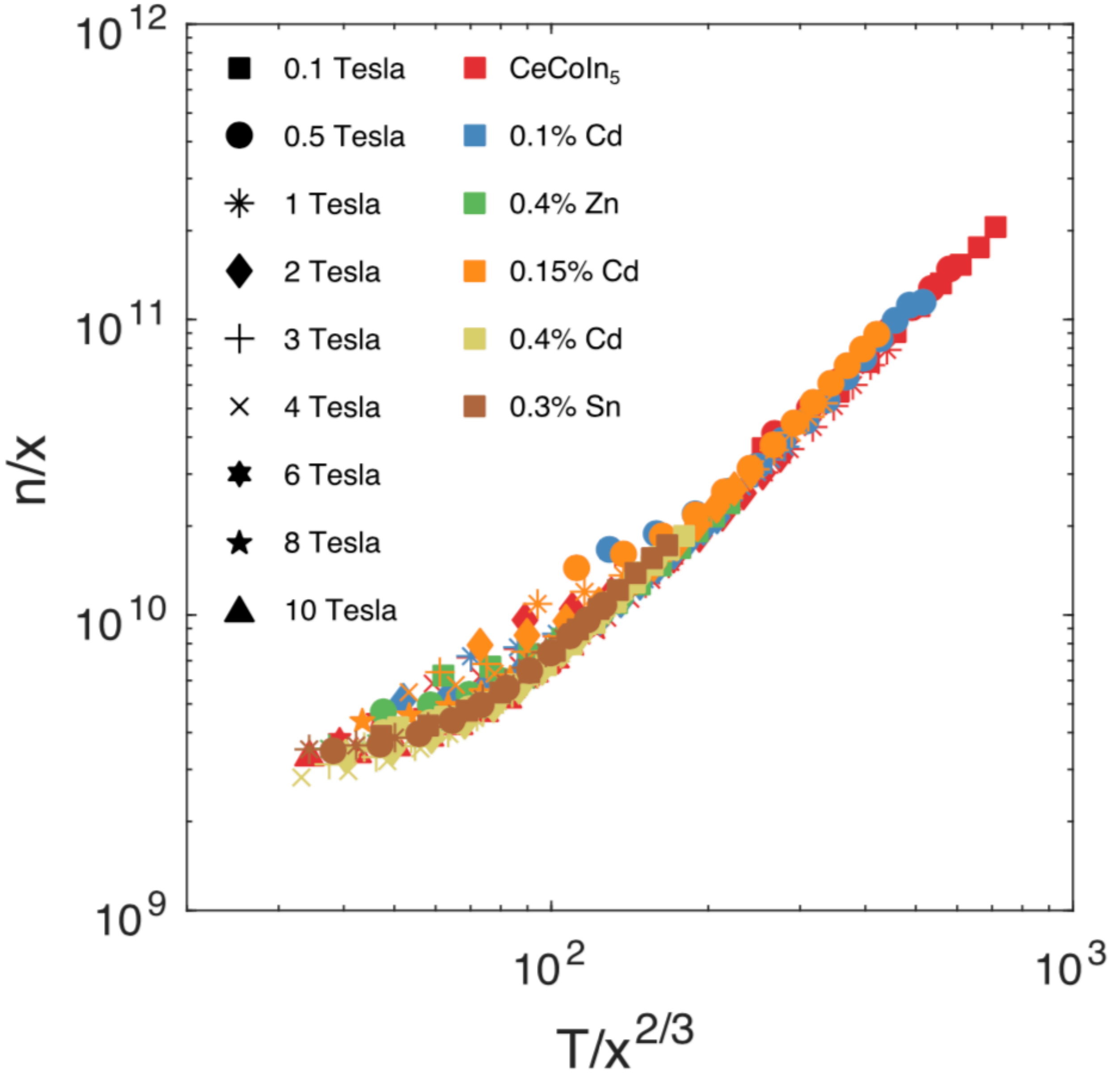




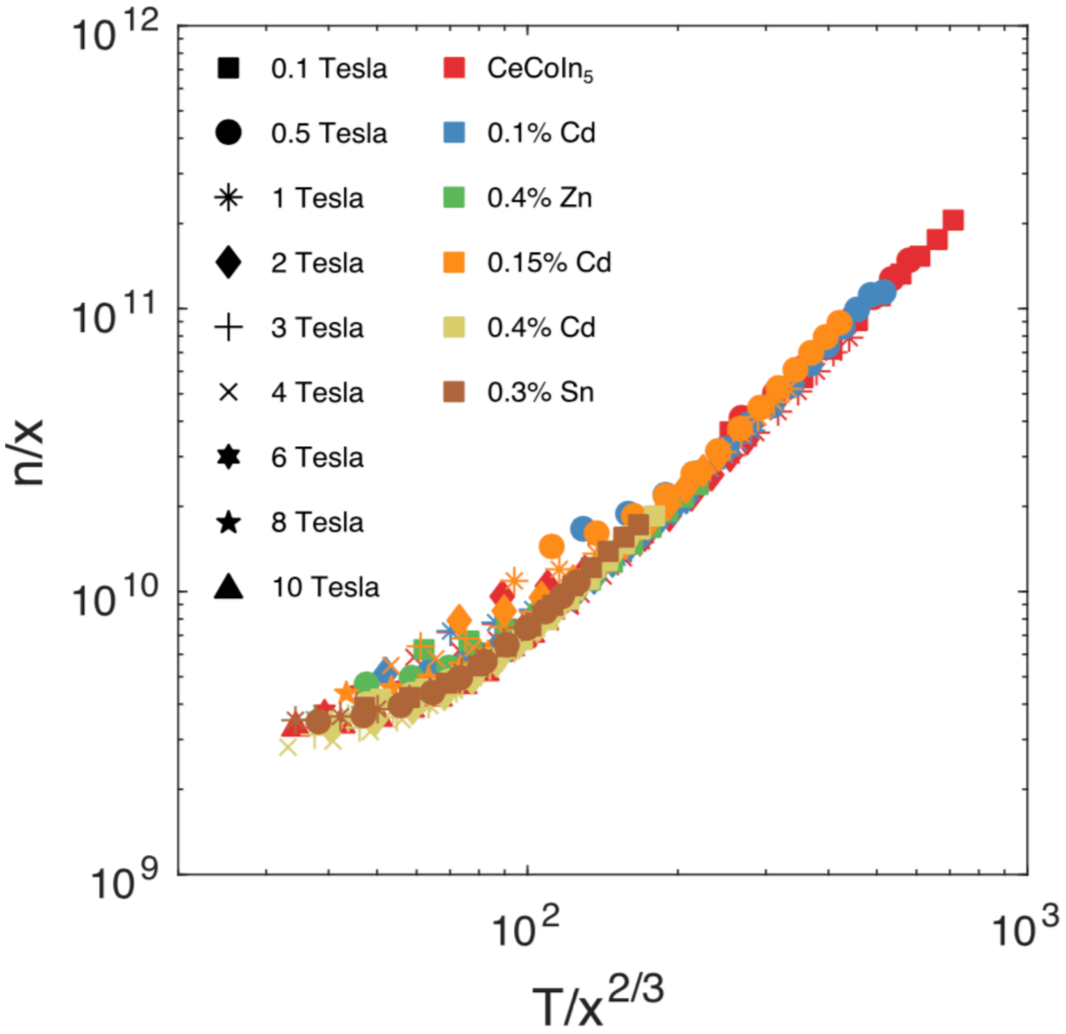
- ➤ **Hall resistivity coefficient measures a diverging correlation function?**
- ➤ **Magnetic field tunes ground state**

Universality in the non-Fermi liquid Hall effect





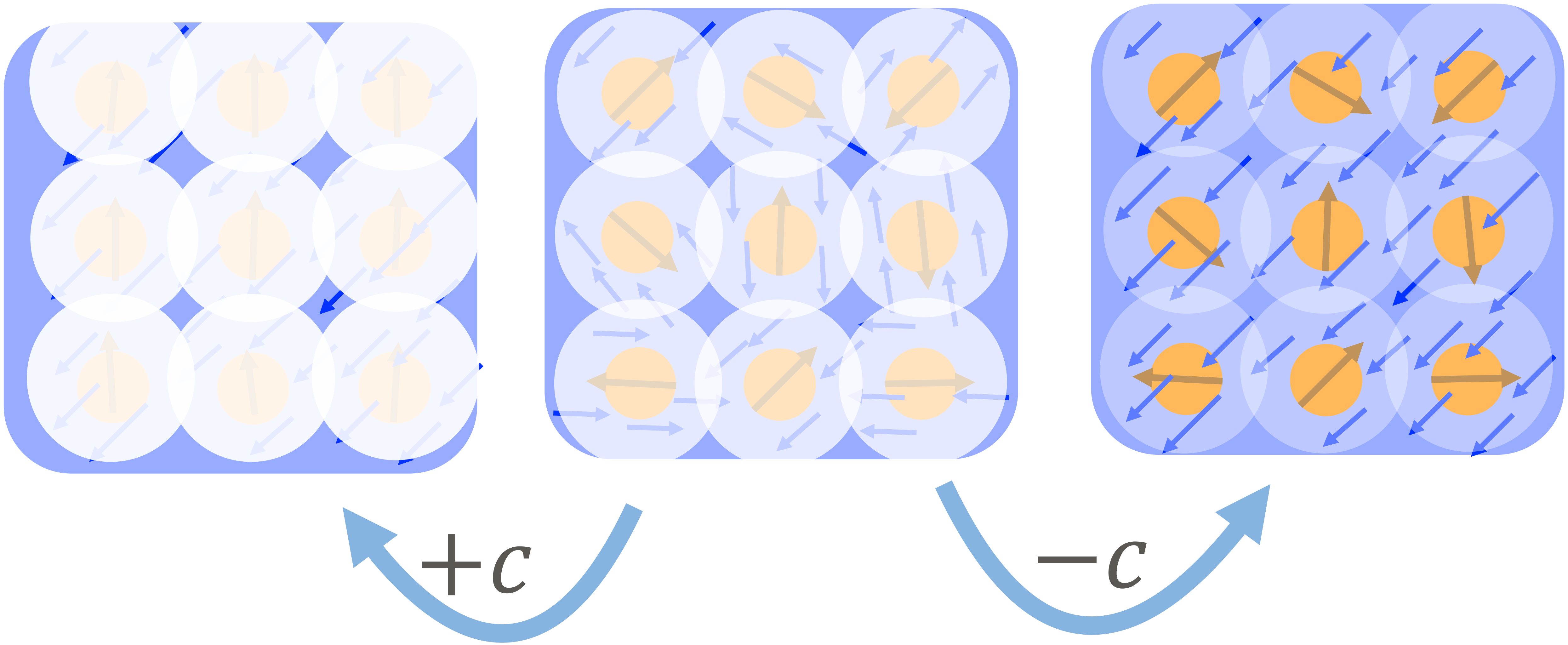
Universality in the non-Fermi liquid Hall effect



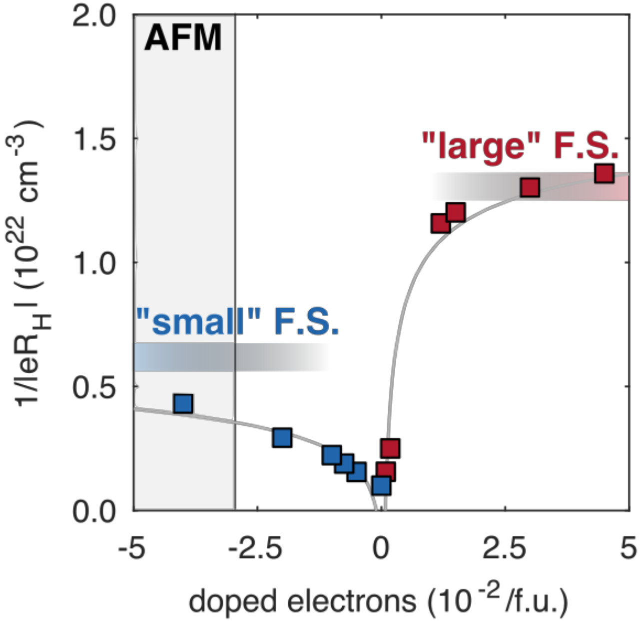
- $n \sim 1/eR_H$,
- x2/3 could be meaningful – condensation of bosons?

$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{m k_B}$$

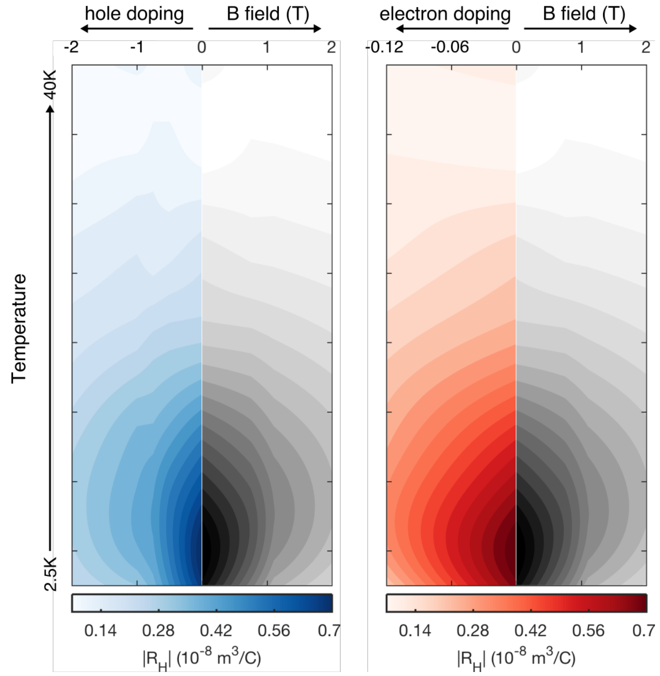
Could fluctuations in the hybridization field be destroying quasiparticles?



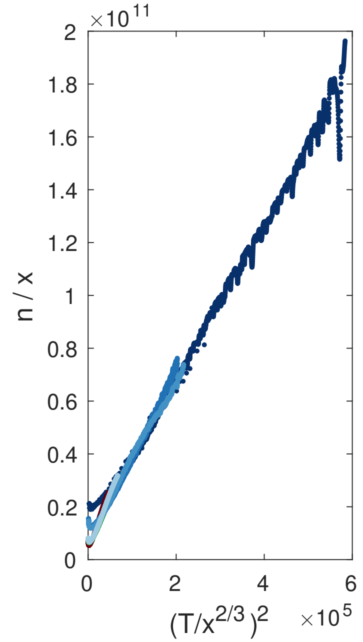
Summary



Vanishing quasiparticles

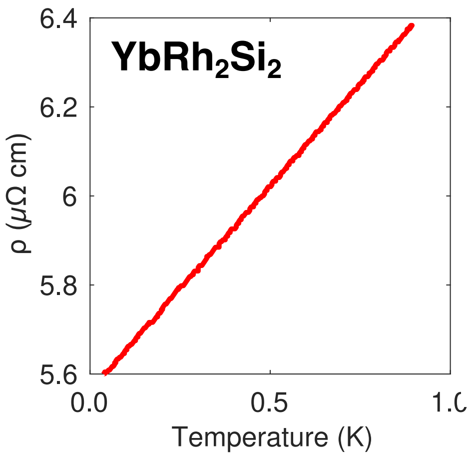


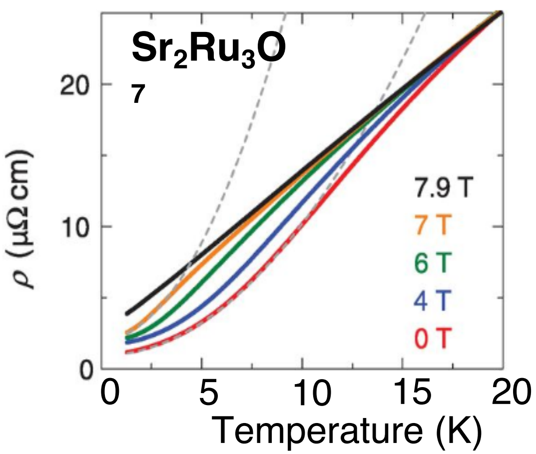
Single energy scale

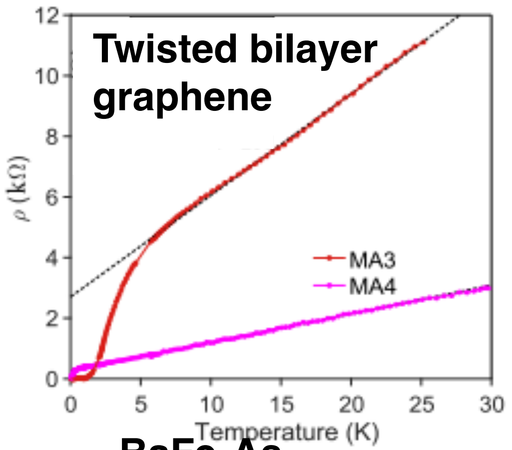


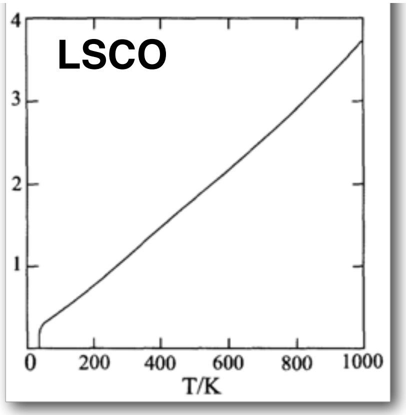
Scaling

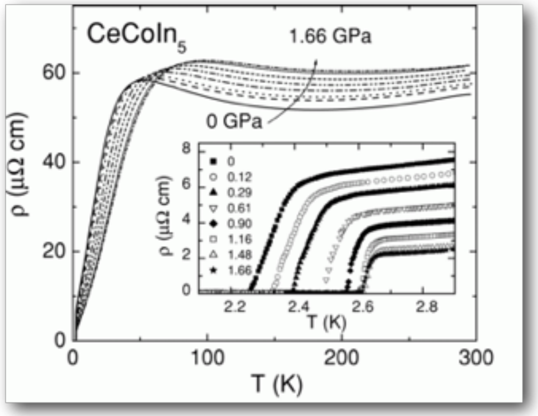
What about everyone else?

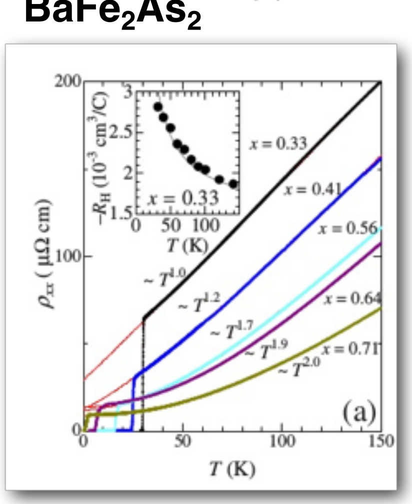






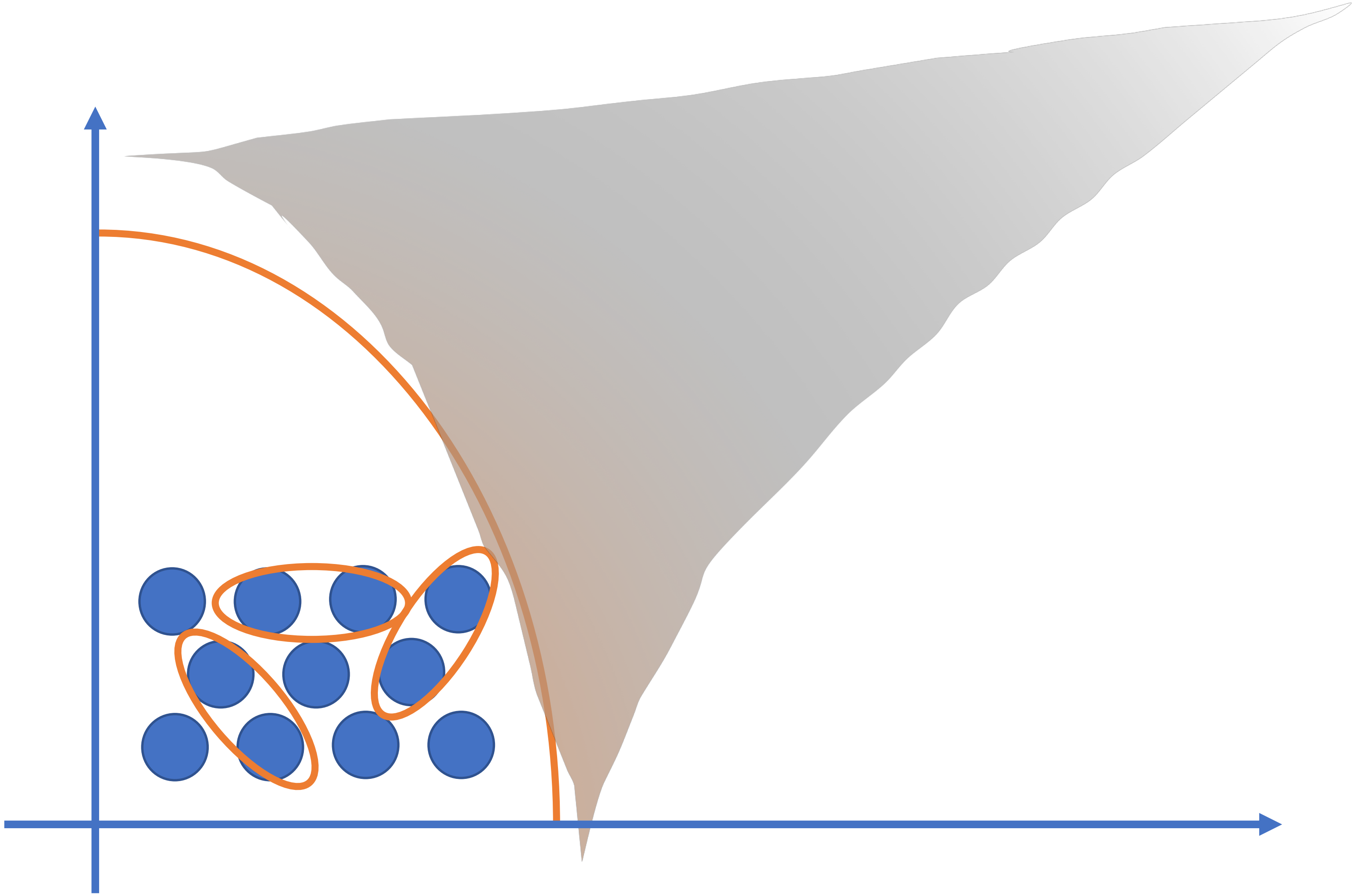






Summary

- The critical straddled by CeCoIn5, appears to connect two Fermi liquids, with large and small FSs
- The Hall number is proportional to a single energy scale that vanishes at this critical point, leading to scaling behavior.
- The hybridization field is the natural "order parameter," fluctuations of which lead to the destruction of quasiparticles.
- With no known magnetically order on either side of the critical point, the appearance of a fractional FL* seems possible.



Thanks!

Berkeley
UNIVERSITY OF CALIFORNIA